

Quantification of Leak Rates Through
Holes in Landfill Liners

Texas Agricultural Experiment Station
College Station

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Quantification of Leak Rates Through Holes
in Landfill Liners

by

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FOREWORD

Today's rapidly developing and changing technologies and industrial products and practices frequently carry with them the increased generation of solid and hazardous wastes. If dealt with improperly, these materials can threaten both public health and the environment. Abandoned waste sites and accidental releases of toxic and hazardous substances to the environment also have important environmental and public health implications. The Hazardous Waste Engineering Research Laboratory assists in providing an authoritative and defensible engineering basis for assessing and solving these problems. Its products support the policies, programs, and regulations of the Environmental Protection Agency, the permitting and other responsibilities of State and local governments, and the needs of both large and small businesses in handling their wastes responsibly and economically.

This report describes the relationship between leak flow rate through synthetic liners and the liner characteristics. Leak rate flow models and curves were developed based on laboratory measurements. The flow models will be useful to designers of hazardous waste surface impoundments and landfills and permit reviewers. For further information, please contact the Land Pollution Control Division of the Hazardous Waste Engineering Research Laboratory.

Thomas R. Hauser, Director
Hazardous Waste Engineering Research Laboratory

ABSTRACT

A study was undertaken to evaluate the rate at which liquids leak through flaws in the flexible membrane liner (FML) component of composite FML-soil liners. The variables studied were: flaw size and shape, FML type and thickness, the influence of a geotextile between the compacted soil and the FML, the conductivity of the soil subbase, the liquid head, and the liquid characteristics. Testing was done in 60 cm diameter permeameters. Soils were compacted in the permeameter and overlain with the FMLs to be tested with either round holes, slits, or seam flaws. A 15 cm layer of gravel was placed over the FML to provide ballast, and a head chamber was used to apply as much as 100 cm of head on the FML. Tests were conducted with a gravel subbase to determine the influence of the flaw alone on the flow rate followed by soil subbases having nominal conductivities of $1 \times 10^{-4} \text{ cm s}^{-1}$ and $1 \times 10^{-6} \text{ cm s}^{-1}$. A calculational procedure was developed to simulate the flow rates through the permeameters and was modified to allow calculation of leak rates under field conditions.

The flow of liquids through flaws in FMLs was primarily dependent on the size and shape of the flaw, the liquid head, and the hydraulic characteristics of the subbase. It was nearly independent of the liner thickness, liquid properties, and the presence or absence of an underlying geotextile.

Variability in flow rates through seam flaws and slits was much greater than that through round holes due to the variable hole sizes that could result if the seam or one side of the slit was displaced relative to the other. This resulted in the average leak rates through slit and seam flaws over a gravel subbase to increase over twelve fold when the flaw length was increased by a factor of 3, from 5 to 15 cm.

For soil subbases, the head loss across the system may be divided into the head loss as the liquid enters the hole, the head loss across the hole in the FML, the head loss as the liquid flows laterally between the FML and the soil, and the head loss through the soil. The head loss in the liquid flowing laterally between the FML and the soil depended on the width of the gap between these two media. The gap widths for the 10^{-4} and 10^{-6} soils were estimated from the permeameter data to be 0.015 and 0.002 cm respectively. Thus less permeable soils containing greater amounts of clay form a better seal with the FML and restrict lateral flow of liquids. Gap widths and resultant flow rates were also

decreased by overburden pressure from simulated layers of waste or liquid head.

Evidence was presented which indicated that erosion of the subbase can occur just below a flaw in a FML, particularly when the liquid head is large, as would occur in a lagoon and when the subbase conductivity is greater than $10^{-6} \text{ cm s}^{-1}$.

Graphs are presented from which engineers, landfill and impoundment designers, and permit writers can estimate the potential leakage rates from field installations.

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SECTION 1

INTRODUCTION

There are a variety of FMLs which have been utilized in the past and are presently on the market for lining landfills and surface impoundments. They typically range in thickness from 0.075 cm (30 mil) to 0.30 cm (120 mil) and come in various size sheets and rolls. The materials are installed and seamed in the field to conform to the shape of the impoundment. They are usually installed over a clean smooth compacted soil and often covered with a protective soil layer before waste is placed in the facility. In some installations, a fabric or geotextile is placed on top of the subgrade to protect the FML from being punctured from below.

Despite these precautions, leaks have been detected in many of the facilities lined with FMLs in the past. These leaks may be a result of imperfect seaming, rips, punctures, tears that occur during installation, and failures that result from subsidence or shear failure of the supporting soil after installation.

Giroud (1983) surveyed 29 facilities and found defective seaming in the field to be the most frequent cause of FML failure. In addition, he concluded that the quality control of installation has not been adequate and that installation crews are often not properly trained. The Office of Technology Assessment (1980) listed the three most common modes of liner failure as improper welding of seams, local deformations due to poor preparation of the liner subbase, and tears and punctures often caused by vehicular traffic during installation.

Whatever the cause of the leaks, it is apparent FMLs in field installations are leaking. Montague (1981, 1982) indicated that three FML lined hazardous waste landfills in New Jersey are leaking. In addition, Brown (1985) reported leakage from 10 of twelve field test cells lined with one type of FML.

Kays (1977) categorized FML failures into those resulting from physical, chemical, or biological failures. Physical failure mechanisms include punctures that may result from traffic pressure even when the liners are covered (Gunkel, 1981), tears, creep, freeze-thaw cracking, wet-dry cracking, differential settling, thermal stress, differential hydrostatic pressure, abrasion, and seam failures (Haxo, 1982). Chemical failure is caused by deterioration that results from ultraviolet light, ozone, hydrolysis, ionic species attack, extraction,

ion species incompatibility, and solvent attack which may dissolve either the plastic or the plasticizer. Biological degradation includes microbial attack, attack by burrowing animals, or damage resulting from animals trying to escape from inside the facility.

FMLs have been successfully used for lining water reservoirs and for retaining hazardous waste in open ponds, where only one set of specified chemicals comes in contact with a carefully selected material, and constant surveillance and monitoring is possible. Facilities that have functioned well for years have been known to fail rapidly if exposed to chemicals for which they were never intended. After testing 12 FMLs with a series of hazardous industrial wastes, Haxo (1980, 1982) concluded that "there does not appear to be any single lining material now commercially available which is suitable for long-term impoundment of all wastes". He also concluded that despite his laboratory tests, field tests are still needed to develop data that allow the extrapolation of laboratory data to the field. The very limited data available on exposed membranes (Haxo, 1982) indicates degradation of materials exposed to landfill conditions for four to nine years. Pacey and Karpinski (1980) suggested that even if FMLs were properly installed so that they did not immediately leak, they would deteriorate 20, 30, or 40 years later. Pertusa (1980) suggested that seven FMLs on which they collected data had useful lives of between 5 and 20 years for water impoundments, and the useful lives would likely be reduced when exposed to wastes.

In one of the few studies of actual field liner systems, Roberts et al. (1983) found that a PVC lagoon liner used for nine years had the following changes in physical properties:

1. The factory seams maintained their integrity well, having 74 to 99% of the shear strength of the material;
2. The field seams did not maintain their integrity well, failing in the adhesive as well as at the seam edge;
3. All seams failed at the glue line in peel tests;
4. Unbonded areas were found in the field seam sections;
5. The field seams had greater shear strength due to greater width, but their peel strength was much lower than the factory seams.

At the present time, there is a dearth of knowledge on leakage rates through flaws in FMLs. It is, therefore, important that these leakage rates be quantified and the principles governing leakage rates be understood so that predictions of leakage rates can be made. Leaks in new installations may result from improper seaming, punctures from overlying or underlying sharp objects such as stones, dropped or

carelessly handled objects such as buckets or hand tools, and traffic such as heavy construction equipment. The leakage rate may be affected by the following parameters:

1. The type of FML,
2. The FML thickness,
3. The size and shape of the flaw,
4. The characteristics of the subbase material,
5. The presence or absence of a geotextile between the subbase and FML,
6. The head of liquid above the flaw, and
7. The characteristics of the liquid to be retained.

The thrust of this research was to evaluate the effect of each of the above factors on leakage rate through flaws in FMLs. Physical measurements of flow rates were made and used to develop a calculational procedure for predicting leakage from any given set of input parameters.

SECTION 2

CONCLUSIONS

1. The flow of liquids through flaws in FMLs was primarily dependent on the size and shape of the flaw, the liquid head and the hydraulic characteristics of the subbase. It was nearly independent of the FML thickness, liquid properties, and the presence or absence of an underlying geotextile.
2. Variability of flow rates through seam flaws and slits was much greater than that through round holes due to the variable hole sizes that resulted from one side of the seam or slit being displaced relative to the other. This caused a 12 fold increase in flow rate when the slit or seam flaw length was increased by a factor of 3.
3. When considering the flow of a liquid through a hole in an FML over a compacted soil subbase, the head loss across the system may be divided into the head loss as the liquid enters the hole, the head loss across the hole in the FML, the head loss as the liquid flows laterally between the FML and the soil, and the head loss through the soil. The head loss as the liquid flows laterally between the FML and the soil was found to be dependent on the width of the gap between the FML and the soil. This gap was estimated from the measured flow rates to be 0.015 and 0.002 cm for the 10^{-4} and 10^{-6} soils, respectively. The gap was independent of flaw size and shape but was affected by overburden pressure.
4. It was observed that soils containing larger amounts of clay and less sand had smaller gap widths between the FML and soil and thus formed a better seal and restricted flow rates.
5. A calculational procedure was developed to extrapolate the permeameter data to field conditions. Graphs of the predicted flow and radius of wetted area from various sizes of round holes in FMLs overlying soils of various conductivities under field conditions are presented. These plots could be used to estimate the number and or sizes of flaws present in a field installation if the total leak rate is known. They can also be used to estimate the number and size of flaws that could be tolerated under specific field conditions to keep the leak rate within a specified range. The graphs also can be used to determine under what conditions the leak rate is such that the presence of the FML is superfluous and the entire soil surface underneath the FML is wetted.

6. The presence of overburden pressure resulting from layers of waste or liquid head served to decrease the gap width between the FML and the soil and thus restricted leak rates. Overburden pressure equivalent to 15.9 m of liquid head decreased the gap width by a factor of 10 and the flow rate by a factor of 100.
7. Evidence was developed which indicated that erosion of the soil subbase can occur immediately below a flaw in a FML, particularly when the liquid head is large, as would occur in a lagoon, and when the conductivity of the subbase soil is greater than 10^{-6} cm s⁻¹.

SECTION 3

RECOMMENDATIONS

1. To decrease the leak rates resulting from flaws in FMLs, every effort should be made to minimize the size and frequency of flaws, and whenever possible the FML should be installed over the smooth surface of a well compacted soil with low hydraulic conductivity.
2. The calculational procedure developed here to allow extrapolation of laboratory permeameter data to field conditions has only been calibrated for small heads and very small holes. Thus, to validate the procedures additional tests under field conditions may be desirable.
3. Erosion of the soil subbase could result in catastrophic failure if the support for the liner is lost. Thus, further research on the factors influencing and methods of curtailing such erosion should be undertaken.
4. Further investigation is needed to verify and elucidate the controlling factors of the relationship between the subbase grain size, overburden pressure, and gap width between the FML and subbase.

SECTION 4

MATERIALS AND METHODS

EXPERIMENTAL PROCEDURES

Large samples of commercially available FMLs were acquired for this study. The materials included the following: 0.05 and 0.08 cm thicknesses of polyvinylchloride (PVC); 0.08, 0.20, and 0.25 cm thicknesses of high density polyethylene (HDPE); 0.08 cm ethylene propylene rubber (EPDM); and 0.09 and 0.11 cm thicknesses of chlorosulfonated polyethylene (CSPE, trade name Hypalon). In addition to these, the following four samples of nonwoven geotextiles were acquired: Hoescht 1127, Hoescht 1135, Foss 65, and Foss 90. Hoescht 1127 and Foss 90 were chosen for use in the experiments. Since there were no significant differences in their performance, only average values are reported. The manufacturer's data on the physical properties of the geotextile materials are given in Table 1. Physical properties

TABLE 1. PHYSICAL PROPERTIES OF THE GEOTEXTILES USED IN THIS STUDY

Properties	Geotextiles			
	Hoescht		Foss	
	1127	1135	65	90
Fabric weight (g cm^{-2})	0.027	0.034	-	-
Thickness (cm)	0.32	0.38	0.25	0.28
Grab strength (Kg)	118/102	154/136	57	82
Grab elongation (%)	85/90	90/95	100	100
Trapezoid tear strength (Kg)	45/43	59/59	30	50
Puncture strength - 5/16" (Kg)	57	70	23	57
Mullen burst strength (MPa)	2.6	3.5		
Vertical water flow (L sec ⁻¹ cm ⁻²)	1.9×10^{-2}	1.8×10^{-2}		
EOS	70-100	70+-100+	70-100	120
Abrasion resistance (%)			50	50
Air permeability (cm ³ s ⁻¹)			7.55×10^4	6.84×10^4

and chemical resistance of the FMLs were reported by Haxo (1980). Appropriate amounts and types of cleaners and adhesives for seaming were obtained from the manufacturers, except for the HDPE which was heat seamed at the factory to our specifications.

Prior to testing, a portion of each liner material was cut into squares 66 cm on a side. Each square was numbered, and the desired flaw was created in the center. Testing included flaws consisting of round holes with diameters of 0.08, 0.16, 0.64, and 1.27 cm. These were made by drilling through the material with the appropriate diameter sharp drill while the FML was clamped firmly between two boards. In addition to round holes, 5 and 15 cm long vertical slits were made in selected materials by laying the FML on a wooden surface and striking it with a sharpened metal plate of appropriate length. To simulate faulty seams, pieces of 28 ga. sheet metal were cut in widths of 5 and 15 cm by 20 cm in length and placed between the pieces of FML to prevent adhesion of the materials when the seam was made (Figure 1). After seaming was complete, the metal strips were removed, resulting in a very precise gap in the seam.

The flow of water through these various flaw sizes and shapes was measured using specially constructed permeameters (Figure 2) filled with gravel or soil of known hydraulic conductivity. The gravel had a nominal conductivity of 10^{-1} cm s⁻¹. A kaolinitic clay ore was obtained from a mine in Kosse, Texas which had conductivity of about 1×10^{-1} cm s⁻¹. When this clay was admixed with a washed sand at a ratio of 60:40, a nominal conductivity of 1×10^{-6} was achieved. This mixture will hereafter be designated the 10^{-6} soil. A locally available sandy loam soil with an average conductivity of 1.96×10^{-4} cm s⁻¹ was used and designated the 10^{-4} soil. A particle size distribution for the washed sand is given in Table 2. A complete textural analysis for the sandy soil and the sand-clay mixtures used throughout the experiments is given in Figure 3.

The dry clay ore was pulverized, sieved through a 0.64 cm sieve, and placed in a small cement mixer with the desired amount of sand. The

TABLE 2. PARTICLE SIZE DISTRIBUTION
OF SAND USED TO ADMIX WITH
CLAY

Size Range (mm)	Percent of Sample
Greater than 1.0	21.8
0.5-1.0	35.5
0.25-0.5	38.5
0.1-0.25	4.0
Less than 0.1	0.2

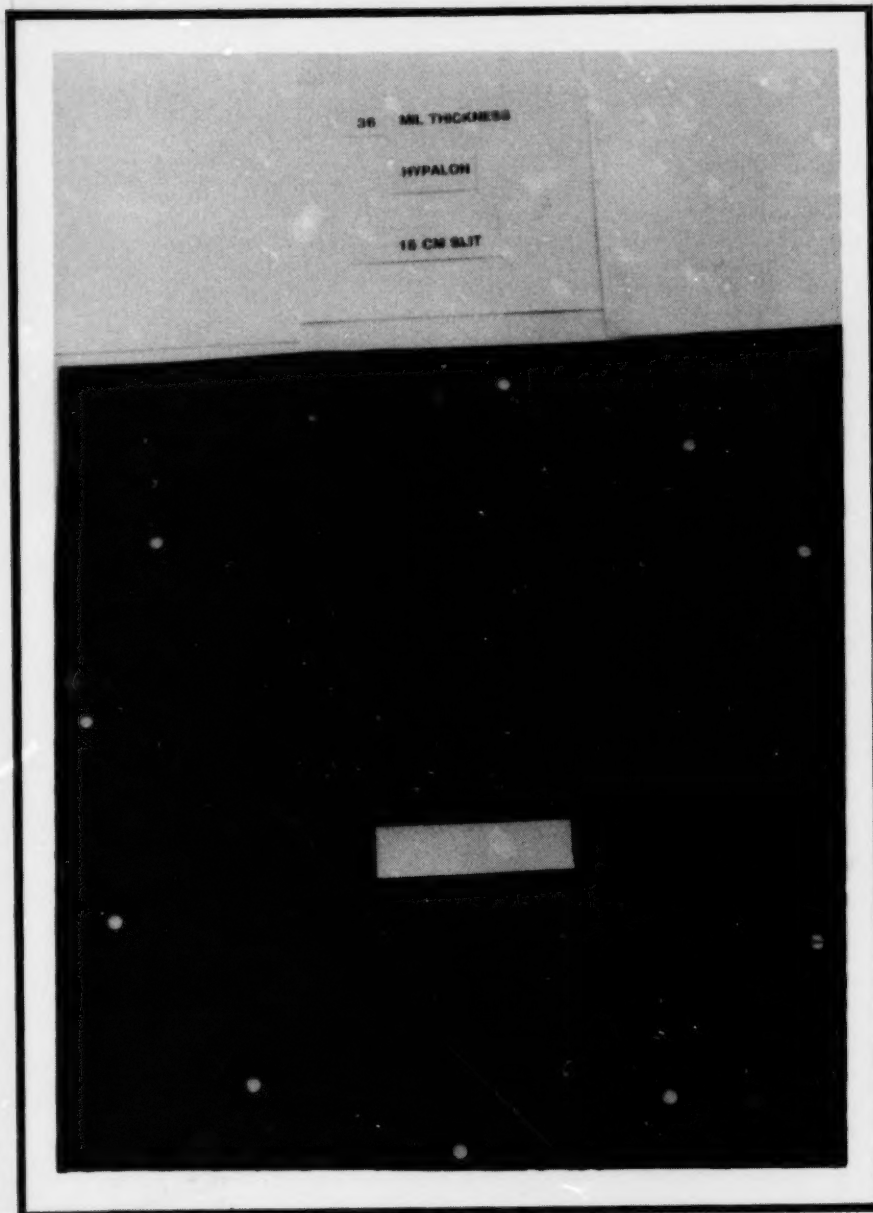


Figure 1.. Photograph of 0.09 cm CSPE with a 15 cm long seam flaw.

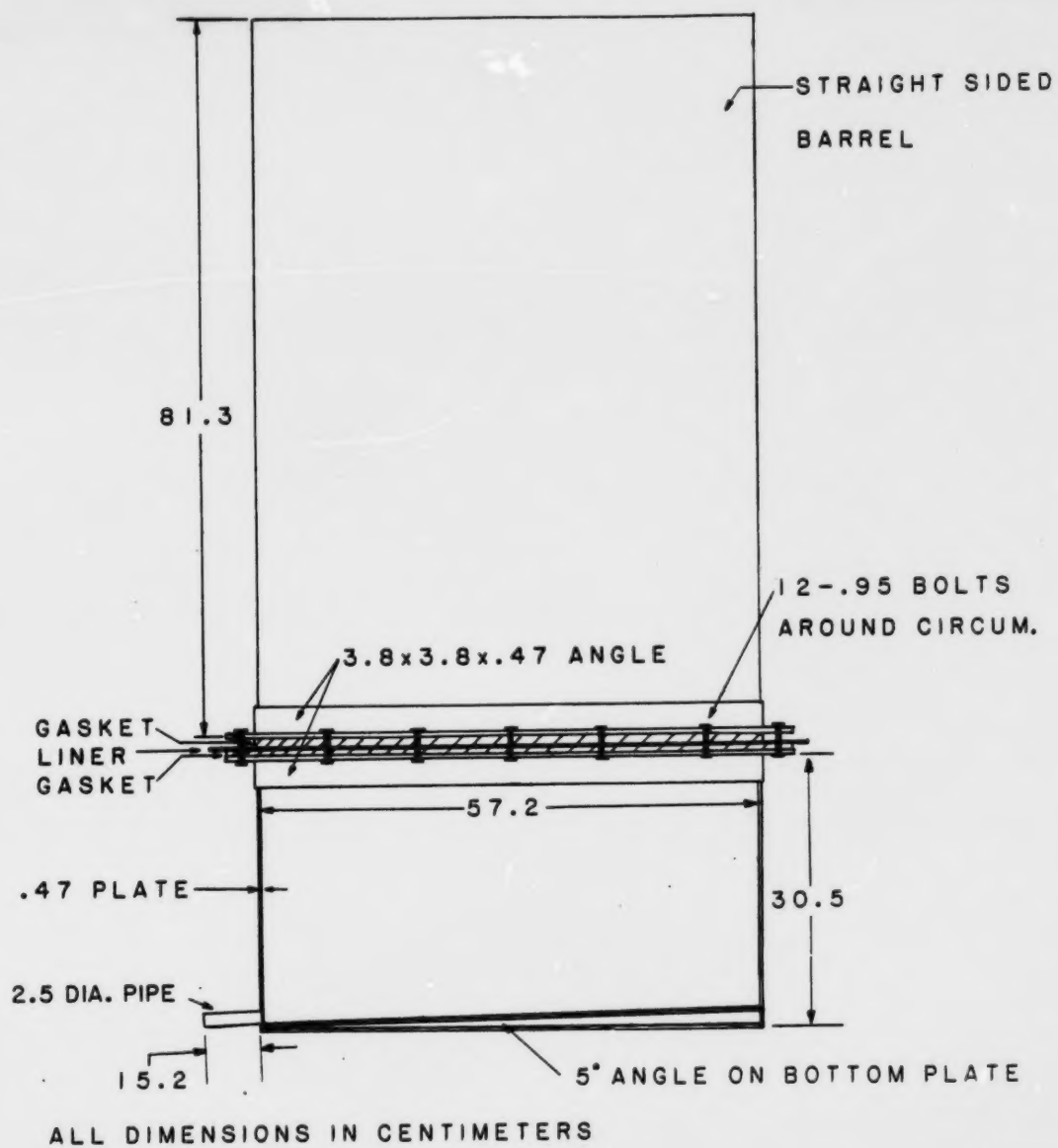


Figure 2. Schematic diagram of a permeameter.

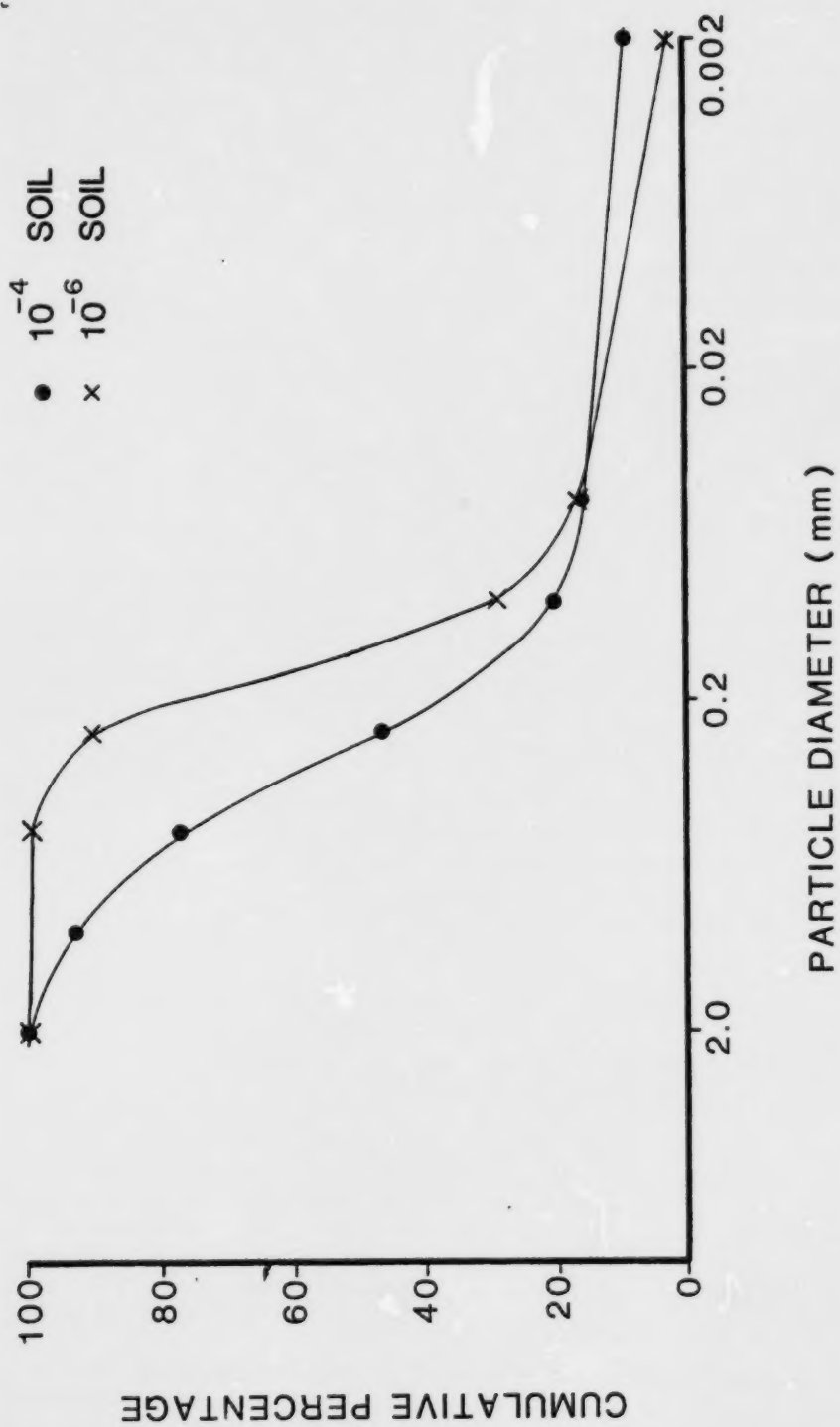


Figure 3. Particle size distribution for the soils used in this study.

mixture was first mixed dry; water was then added until the optimum moisture content for compaction was achieved. Each mixer batch was individually tested for moisture content to assure uniformity. Prior to placing the soil in the permeameter, the outflow hole was covered with a fine screen, and a two cm deep layer of 0.64 cm gravel was then placed in the bottom of each permeameter to allow for the free drainage of leachate. The soil was added in 15 to 20 L increments. Each soil addition was compacted using an electric reciprocal packer (Bosch Model 11305) equipped with a 15 x 15 cm square foot (Figure 4). The surface was then lightly scarified, and the next increment of soil was added and compacted. This procedure continued until the permeameter was filled to about one cm above the top rim. The excess soil material was then carefully scraped off to yield a full permeameter base. A gasket was placed on the permeameter base flange. If the test required a geotextile under the FML, a 60 cm diameter piece of the appropriate material was cut and positioned over the soil. The FML section with the flaw to be tested was positioned over the permeameter. The head tank, an open ended straight sided drum, and a gasket were set on the liner, and a flange was slipped over the tank and bolted in position. A 15 cm square piece of 0.3 cm mesh screen was placed over the flaw to prevent gravel from blocking the hole or slit. Fifteen cm of 1.9 cm diameter gravel was placed over the FML to provide ballast weight and prevent the liner from floating. The head tank was then filled to the appropriate depth, usually 90 to 95 cm, with water or other liquid to be tested. A Stevens type F water stage recorder was used to record the decrease in water level with time. Except for two small openings for the recorder cables to pass, the top of the head tank was covered with plastic to minimize evaporation. When changes in head were too small to measure, a float valve was used to meter the water into the head tank. For this procedure, the water stage recorder was used to measure the head drop in a 14 cm diameter stand pipe. The conductivity of soil in the absence of a liner was periodically measured by the same procedure. Thus, any intrinsic changes in the soil conductivity could be deleted from the treatment effects.

The majority of the tests were conducted with tap water as the permeant; however, a small number of tests employed synthetic landfill leachate, as described by Ham *et al.* (1979), and waste xylene as permeants.

To assess the effects of liquid heads greater than those which could be achieved using the head tank, the pressure vessel shown in Figure 5 was used. This vessel was bolted on the permeameter in place of the head tank and could be used to apply up to 0.1 MPa to the liquid surface. This pressure approximated a liquid depth of 10 m. Readings of flow rate were made through the sight tube connected to the 10.1 cm inside diameter tube.

The apparatus shown in Figure 6 was used to assess the effects of overburden pressure on the leakage rate in a limited number of tests. The springs were used to provide a steady compression force on the



Figure 4. Subbase soil being compacted in permeameter base.

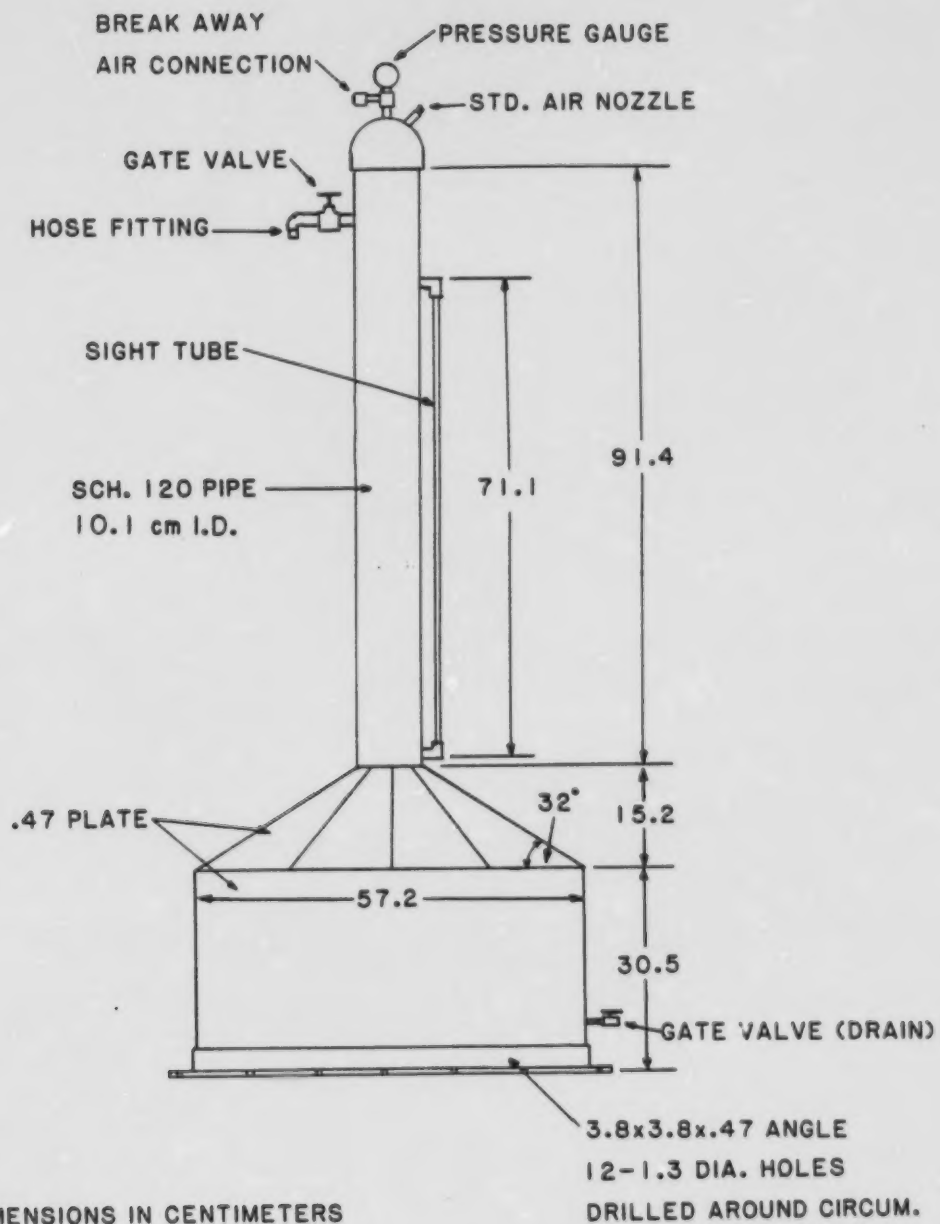


Figure 5. Schematic diagram of the pressure top.

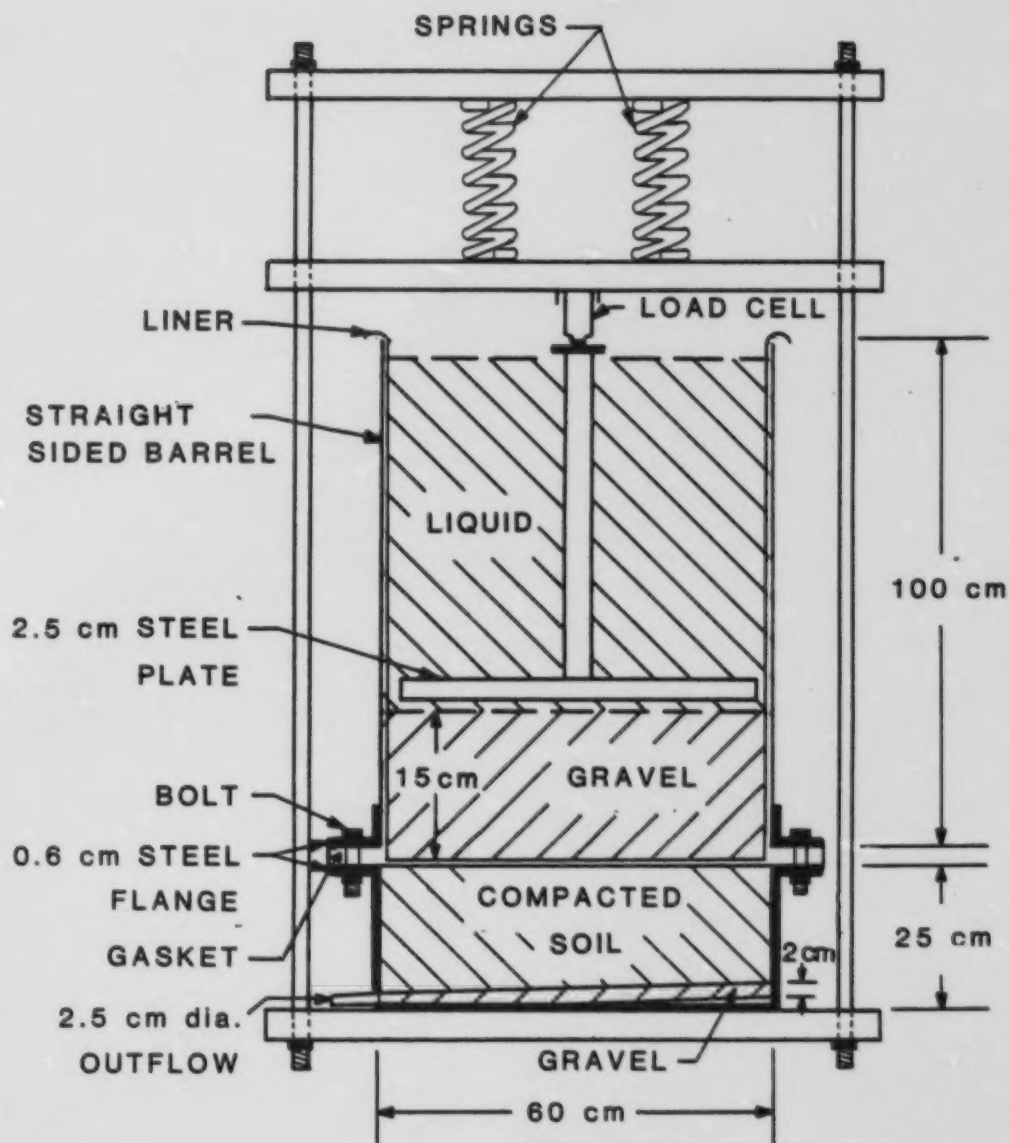


Figure 6. Schematic diagram of a permeameter modified to apply overburden pressure.

piston in the apparatus. The equipment was used to apply an overburden pressure of 156 kPa to the FML above the soil surface. Since the soil was expected to consolidate, the FML was not put between the gaskets. It was instead shaped into a large bag to allow vertical movement. This configuration was used to minimize distortion of the flaw shape when the pressure was applied. Because of the need to shape the FML to the head tank, these tests could only be done with the EPDM material.

Since it was not practical to test all the possible combinations of liner materials, liner thickness, hole size and shape, and subbase conductivity, only selected combinations of parameters were tested as shown in Table 3. Three or more replications of each set of parameters indicated on the table were run. These include all hole sizes and shapes in the 0.08 cm HDPE liner over gravel 10^{-1} , 10^{-4} and 10^{-6} cm s $^{-1}$ subbase, and all hole sizes and shapes in the 0.09 CSPE over the 10^{-6} cm s $^{-1}$ subbase only. The 10^{-4} and 10^{-6} conductivities listed are nominal conductivities since the actual conductivity of the compacted soil subbase which were used differed slightly from the nominal values. Therefore, the calculational procedure described in Appendix A was developed to reduce the data and remove the differences due to the varying subbase conductivities and to allow extrapolation to conditions which were not measured. The individual recorded data are given in the latter part of Appendix A.

Measurements were made for all three subbases for 0.04 cm diameter holes in all thicknesses of each liner evaluated. Additional measurements were made on the 0.25 cm thick HPDE for 0.16 and 1.27 cm diameter holes over all three subbases and for the 0.08 cm thick EPDM with 0.08 and 0.16 cm diameter holes over gravel to allow closer observation of the behavior of these particular liner materials.

MATHEMATICAL MODEL FOR DETERMINING LEAKAGE RATES

The variables that control the leakage rate through liner flaws include the fluid head, hole size, hole shape, subsoil conductivity, leachate characteristics (viscosity, density), and FML characteristics (thickness, flexibility). To determine the influence of each of these variables on the leak rate, it was necessary to develop a model that simulates the actual flow mechanism. The various steps involved in assembling the components of the model are described below. The mathematical derivations of the model are given in Appendix A. The actual model and users guide are given in Appendix B.

Development of this model was accomplished in two separate steps. First, a calculational procedure was developed based upon the flow and boundary conditions including the sidewalls that exist within the laboratory permeameters. This model was then calibrated using the permeameter data. Subsequently, the boundary conditions of the model and the assumptions regarding infiltration rates were modified so that they would be representative of field conditions. The possible

TABLE 3. THE COMBINATIONS OF FML MATERIAL, LINER THICKNESSES, SUBBASE CONDUCTIVITIES AND HOLE SIZES AND SHAPES WITH WATER AS THE PERMEANT*

Hole Size and Shape	Subbase Conductivity (cm s ⁻¹)	HDPE Thickness (cm)			PVC Thickness (cm)			CSPE Thickness (cm)			EPDM Thickness (cm)		
		0.08			0.05			0.09			0.11		
		10 ⁻¹	10 ⁻⁴	10 ⁻⁶	10 ⁻¹	10 ⁻⁴	10 ⁻⁶	10 ⁻¹	10 ⁻⁴	10 ⁻⁶	10 ⁻¹	10 ⁻⁴	10 ⁻⁶
0.08 cm dia rnd		x	x	x							x		
0.16 cm dia rnd		x	x	x							x		
0.64 cm dia rnd		x	x [†]	x							x		
1.27 cm dia rnd		x	x	x							x		
5.1 cm slit		x	x	x							x		
15.2 cm slit		x	x	x							x		
5.1 cm seam		x	x	x							x		
15.2 cm seam		x	x	x							x		

* The combinations tested are indicated by (X).

† Also tested using xylene and synthetic landfill leachate as the permeant.

†† Also tested under 4086 kg overburden pressure.

confining effect imposed by the permeameter walls were thus removed. The second model was then used to obtain a set of graphs that can be used to determine the leakage rate that occurs in a field installation when the subsoil conductivity, the liquid depth and hole size are known.

An important observation made during the experimental study was that the leachate passing through the hole spread laterally between the liner and the top of the subsoil. Under these flow conditions, the liquid will infiltrate into the subsoil over a much larger area resulting in a higher leak rate. Therefore, in estimating leakage rates, it would be too conservative to assume that a seal formed between the liner and the soil without a gap through which lateral flow can occur. Thus, it was necessary to take the gap width into consideration when the calculational procedures were developed. The models are thus capable of analyzing a flow situation where liquid flows laterally through a gap between the liner and subsoil and infiltrates into the soil simultaneously. The gap width between the liner and the subsoil may depend on the overburden pressure, the stiffness of the liner and the particle size of the subsoil. The gap width cannot be determined by direct measurement and was therefore estimated by a back calculation process using the observed flow rates.

SECTION 5

RESULTS AND DISCUSSION

GRAVEL SUBBASE

Effects of Flaw Size and Shape

Testing of flow rates through various sized round holes in 0.08 and 0.25 cm thicknesses of HDPE over a gravel subbase was done to evaluate the effect of flaw size without a limiting subbase. Detailed data are given in Appendix A. The gravel subbase had a conductivity of 0.13 cm s⁻¹ and was not limiting to the flow through any of the holes tested in the FML. Thus, these measurements represent the maximum amount of liquid that could flow through the given flaws. Since all measurements were not taken at the same heads, the data were fit to a straight line by linear regression, and the flows for 50 and 100 cm heads were calculated from the resulting equations. Plots of the flow rates at these two heads are shown in Figures 7 and 8 for the 0.08 and 0.25 cm thicknesses of HDPE, respectively. As expected, discharge increased greatly as the area of the hole increased. The increase was curvilinear and resembles published data for discharge from pipes (Barfield *et al.*, 1981). A doubling of the head from 50 to 100 cm resulted in a significant increase in discharge for both liner thicknesses but did not double the discharge rate.

The flow rates of water through slits and seam flaws in 0.08 cm HDPE are given in Table 4. While insufficient data were available to run statistics on the 5 cm slits, it is quite apparent that the flows through the 15 cm slits were much larger. Likewise for the seam flaws, the flows from the 15 cm flaws were much greater than those from the 5 cm flaws. Significant differences ($P = 0.05$) were found at a 50 cm head, while the 100 cm head differed only at the 0.10 level. The data for both slits and seams were highly variable, as evidenced by the large standard deviations Table 4. Visual observations indicated that small changes or differences in the manner in which the liner laid on the subbase could alter the width of the slit or seam opening and, thus, greatly change the flow rate.

Effect of Material Type

Discharge rates through 0.64 cm diameter round holes in the 0.08 to 0.09 cm thicknesses of four materials at two hydraulic heads suggested that there are significant differences ($P = 0.05$) due to material (Table 5).

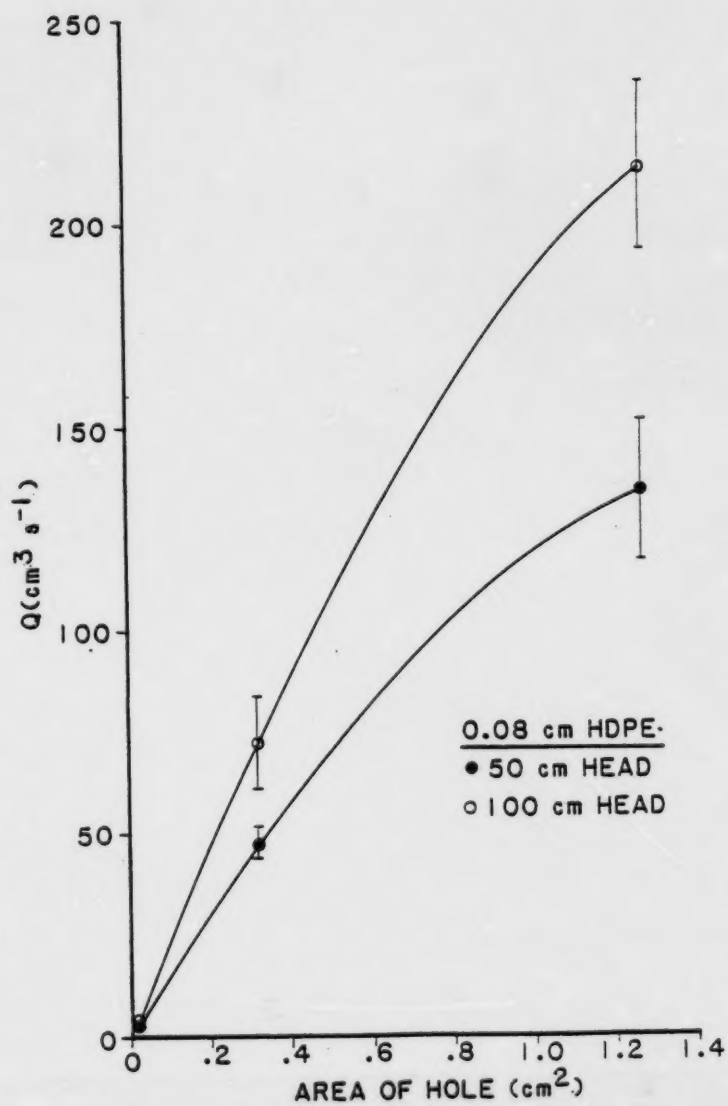


Figure 7. Flow rate of water through various size holes in 0.08 cm HDPE at two heads over a gravel subbase.

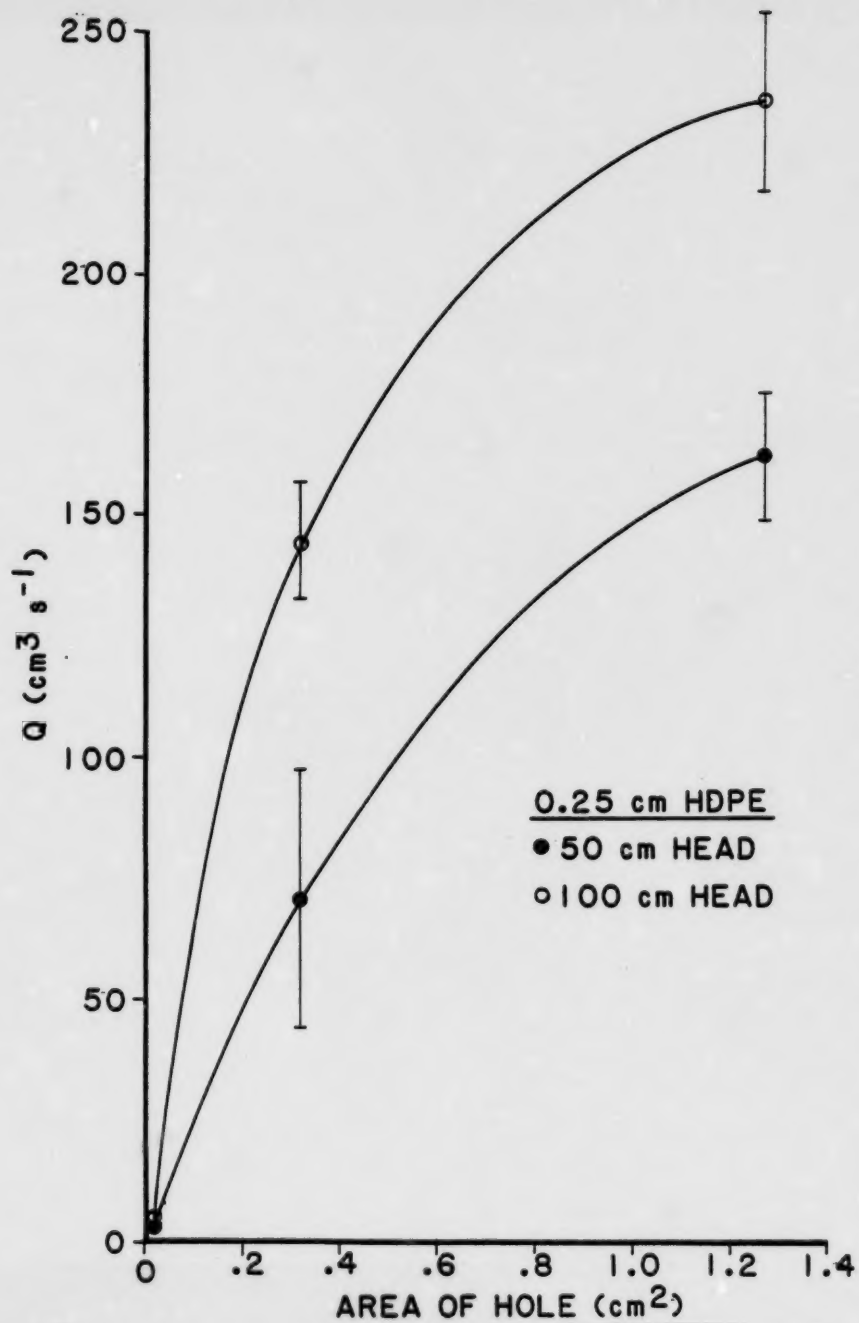


Figure 8. Flow rate of water through various size holes in 0.25 cm HDPE at two heads over a gravel subbase.

TABLE 4. FLOW RATES OF WATER THROUGH SLITS AND SEAM
FLAWS IN 0.08 CM HDPE AT TWO HEADS OVER
GRAVEL SUBBASE.

Flaw	Head (cm)	Flaw Length			
		5 cm		15 cm	
		Mean	S.D. 3^{-1}	Mean	S.D. 3^{-1}
Slit	50			122.6 +	87.1
	100	2.5		178.3 +	83.6
Seam	50	12.8 +	11.1b	149.1 +	83.6a
	100	10.3 +	3.1a	229.7 +	149.5a

Values in any given row followed by the same letter
do not differ significantly at $P = 0.05$.

TABLE 5. MEAN DISCHARGE RATES THROUGH 0.64 CM DIAMETER ROUND
HOLES IN FOUR FMLs.

Head cm	HDPE 0.08 cm	PVC 0.08 cm	CSPE 0.09 cm	EPDM 0.08 cm
	$\text{cm}^3 \text{ s}^{-1}$			
50	48.0a*	26.3b	25.4b	56.9a
100	72.7ab	40.3b	42.3b	96.0a

* Values in a given row followed by the same letter do not
differ significantly at $P = 0.05$.

The PVC and CSPE liners had significantly lower discharge rates than the EPDM at both heads and was significantly lower than the HDPE at the 50 cm head. Thus, the PVC and CSPE materials seem to offer more resistance to flow through a hole and, thus, have greater head loss and lower discharge rates when the flow beneath the liners is unobstructed.

Effect of Geotextile Under the Liner

The flow rates of water through 0.08 cm HDPE liners with round holes are shown in Figures 9 and 10 as a function of hole size with and

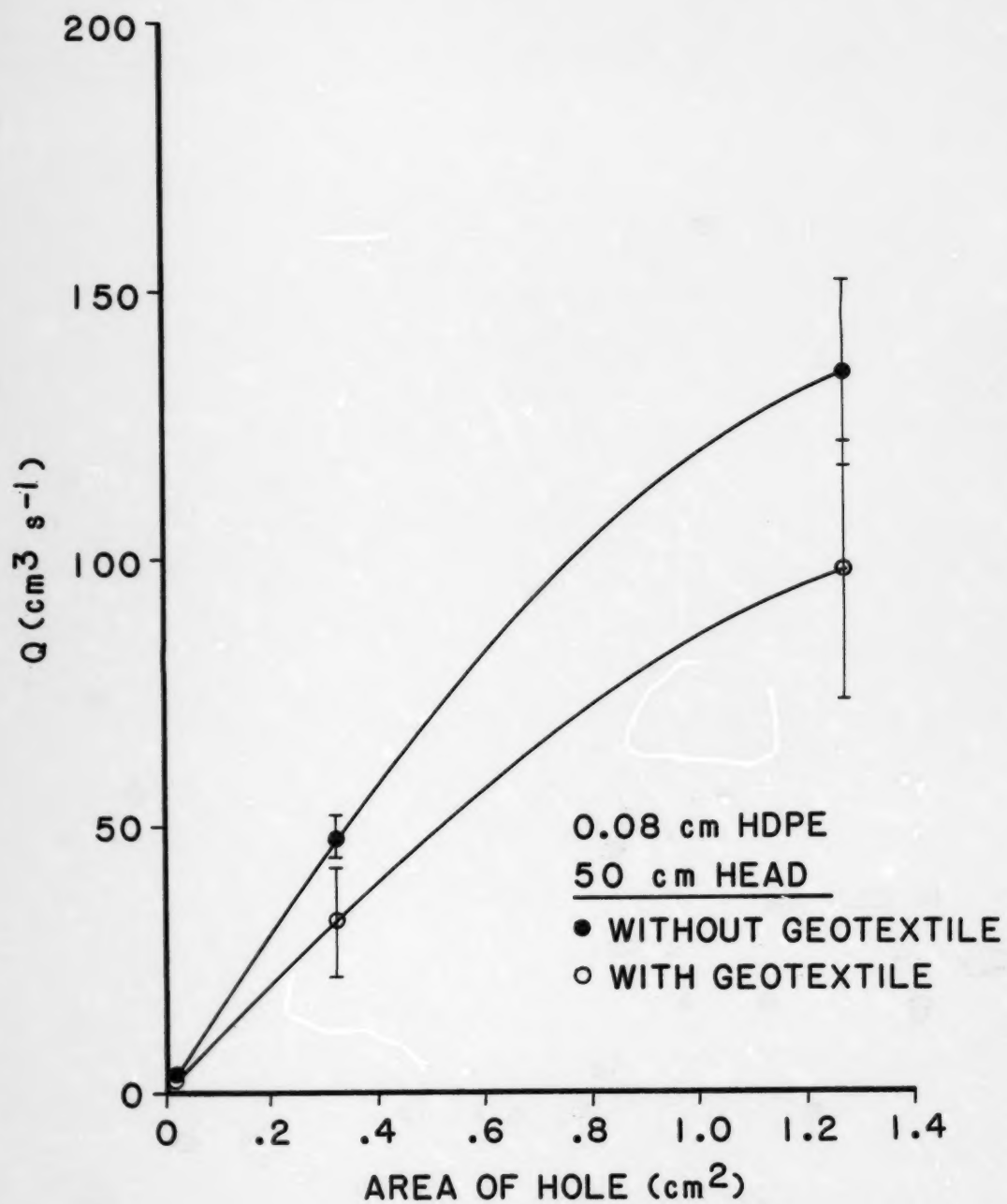


Figure 9. Flow rate of water through various size holes in 0.08 cm HDPE at 50 cm head with and without a geotextile between the FML and gravel subbase.

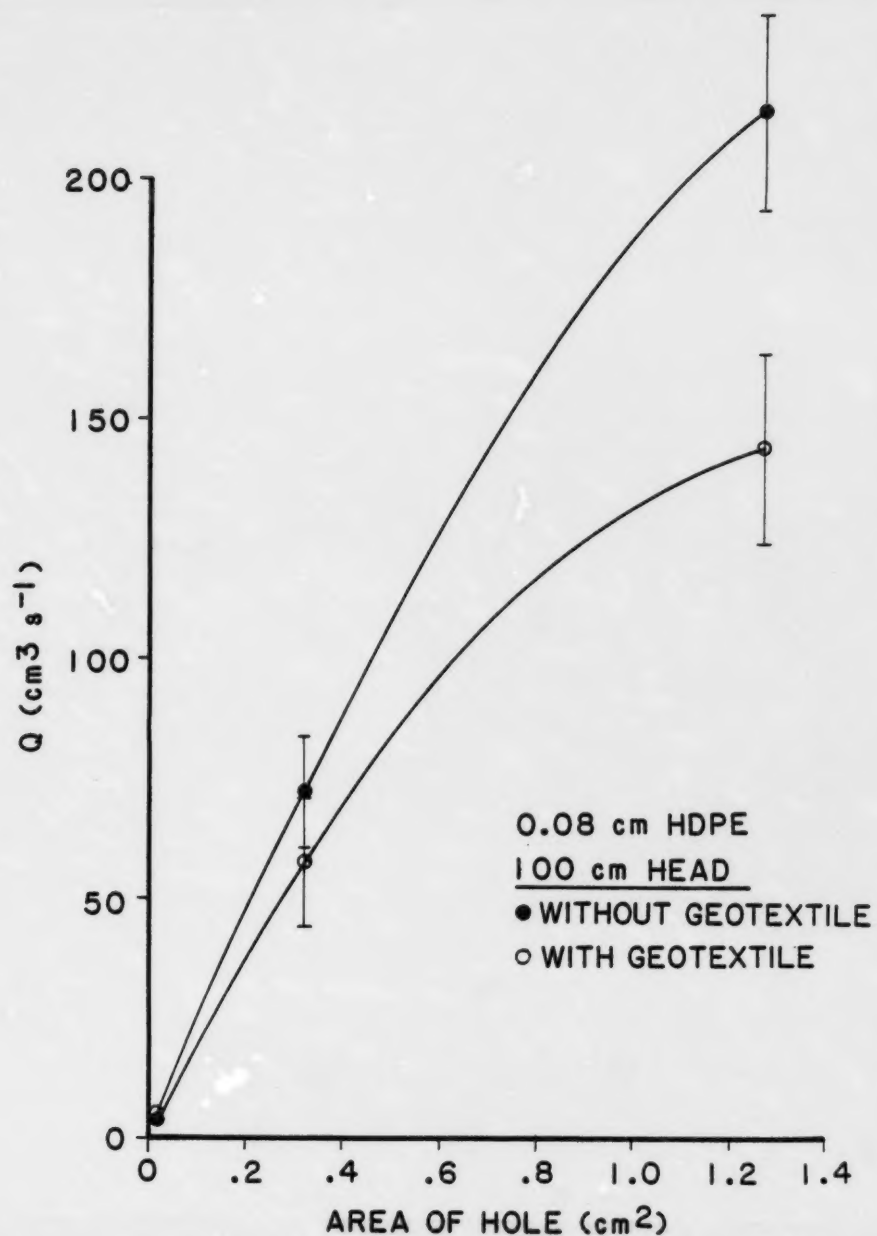


Figure 10. Flow rate of water through various size holes in 0.08 cm HDPE at 100 cm head with and without a geotextile between the FML and gravel subbase.

without a geotextile between the liner and the gravel subbase. At a 50 cm head, the flow rates only differed significantly for the 0.64 cm diameter (0.32 cm² area) hole. At a head of 100 cm, the flow rates were significantly different only at the 1.27 cm diameter (1.3 cm² area) hole. Four of the six sets of data did not differ significantly. The two data sets which did differ were for different hole sizes, suggesting the absence of pattern concerning the impact of geotextiles on flow rates when gravel underlies a defective FML.

Flow rates through 15.2 cm vertical slits in 0.08 cm HDPE over gravel with and without a geotextile showed no significant difference (Table 6). Flow through 15.2 cm seam flaws, however, was significantly decreased in the presence of a geotextile. This was likely caused by the textile bridging the gaps between gravel particles and creating a supporting surface under the liner, thus allowing the gravel overburden to close the seam flaw.

TABLE 6. FLOW RATES OF WATER THROUGH 0.08 CM HDPE WITH AND WITHOUT A GEOTEXTILE BELOW THE LINER AT TWO HEADS

Flaw	HEAD							
	50 cm				100 cm			
	Without		With		Without		With	
	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.
	-----		-----		-----		-----	
15.2 cm slit	122.6	+ 106.6a*	52.6	+ 28.5a	178.3	+ 96.0a	95.1	+ 41.2a
15.2 cm seam	149.1	+ 83.6a	30.9	+ 20.1b	229.7	+149.5a	58.5	+ 29.7b

*Values in a given row at a given head followed by the same letter do not differ significantly at P=0.05.

Effect of Liner Thickness

The effect of liner thickness on the flow rates of water through 0.64 cm diameter holes in liners over gravel is given in Table 7 and Figure 11. At a hydraulic head of 100 cm of water, there was no significant change in flow rate due to liner thickness. At a 50 cm head, there were no significant (P = 0.05) differences in the PVC and CSPE liners.

The flow rate from the 0.08 cm HDPE liner was similar to that from the 0.25 cm thickness, but slower than the flow from the 0.20 cm thickness. This observed difference is opposite to that which would be expected. One possible explanation for the reduced flow in the thin

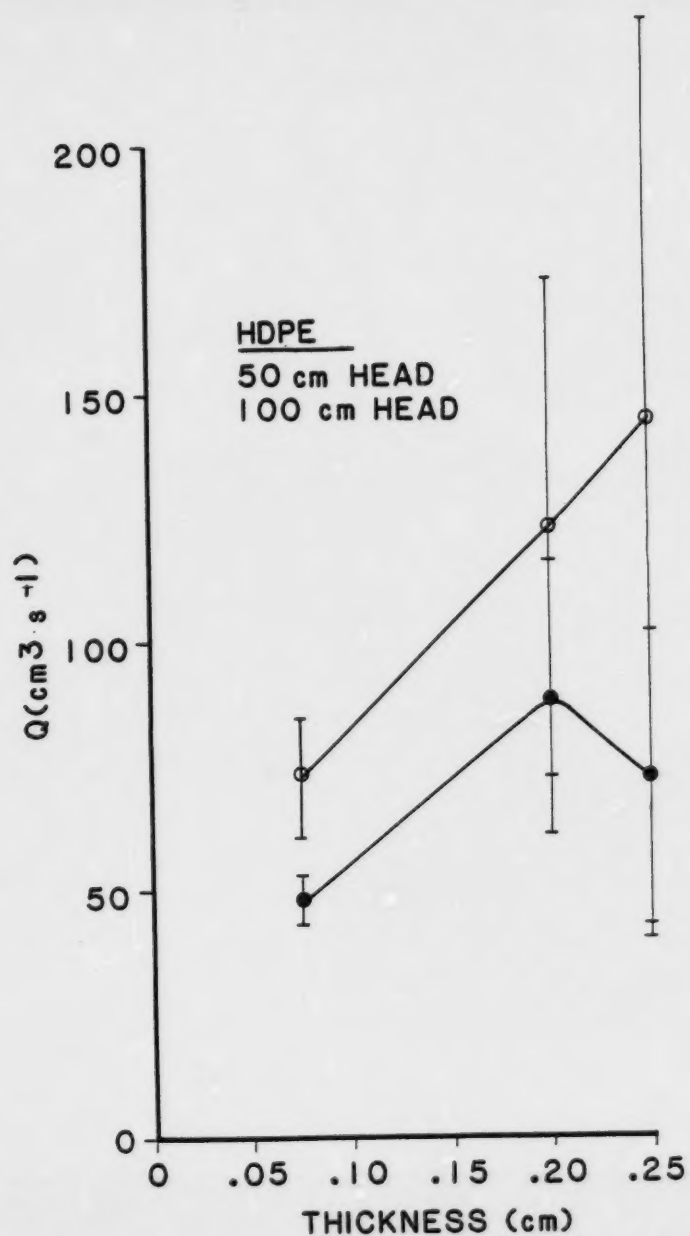


Figure 11. Flow rate of water through a 0.64 cm diameter hole in various thicknesses of HDPE at two heads.

TABLE 7. FLOW RATES OF WATER THROUGH VARIOUS THICKNESS LINERS WITH A 0.64 CM DIAMETER ROUND HOLE OVER GRAVEL SUBBASE

Thickness	Mat'l	HEAD			
		50 cm		100 cm	
		Mean	S.D	Mean	S.D
		cm ³ s ⁻¹			
		-----		-----	
0.08 cm	HDPE	48.0 +	4.8b*	72.7 +	12.7a
0.20 cm	HDPE	89.5 +	27.6a	123.2 +	49.7a
0.25 cm	HDPE	71.1 +	31.1a	145.2 +	82.0a
0.05 cm	PVC	24.9 +	17.3a	33.8 +	20.9a
0.08 cm	PVC	26.3 +	14.8a	40.3 +	21.5a
0.09 cm	CSPE	25.4 +	8.7a	42.3 +	26.7a
0.11 cm	CSPE	49.3 +	17.9a	83.5 +	38.4a

*Values in a given column at a given head for a given material followed by the same letter do not differ significantly at P = 0.05.

material is that it is less rigid and, therefore, may come into closer contact with the gravel subbase material, which could inhibit the flow of liquid through the opening. The present data suggest that as a first approximation the flow rate is independent of the liner thickness when the flow is not restricted by a soil base. Conditions where the flow is limited by the subbase conductivity are discussed in a later section of this report.

Application

Many new hazardous waste landfills and surface impoundments are being constructed with double FML liners with a drainage system between them. For this system to function properly, it is imperative that the drainage system be sized to remove any accumulated liquid as fast as it enters. Table 8 presents the maximum anticipated leakage from different flaw shapes and sizes at two liquid heads. This information may be used as a guide when designing the drainage system for a double lined facility to estimate the amount of liquid which will have to be removed annually.

Summary

Flow through flaws in FMLs over very permeable subbases are highly dependent on flaw size and shape, liquid head, and subbase conductivity.

TABLE 8. MAXIMUM ANTICIPATED LEAKAGE IN $M^3 \text{ YR}^{-1}$ FROM
DIFFERENT SIZE AND SHAPE FLAWS IN 0.08 CM
THICK HDPE LINER AT TWO LIQUID HEADS

Hole Size and Shape	Head (cm)	
	50 $m^3 \text{ yr}^{-1}$	100
0.16 cm diameter	110	145
0.64	1482	2208
1.27	4257	6780
5 cm slit	No Data	79
15 cm slit	3866	5623
5 cm seam	404	325
15 cm seam	4702	7244

The type of FML material made only a small difference with the PVC and CSPE materials having a slightly slower flow rate than HDPE and EPDM materials under similar conditions. The presence or absence of an underlying geotextile made no significant difference in leakage rate from an FML. Similarly, the FML thickness did not significantly affect the leakage rate. A table of anticipated maximum leakage volumes is presented which may be used to design drain systems for new facilities and to estimate the size and number of flaws in existing facilities.

SOIL SUBBASE

Variability of Soil Conductivity

Even with the great care that was taken to develop and use standardized wetting, mixing, and compacting procedures, it was difficult to compact soils in the permeameters which had the exact desired conductivity. In addition, the conductivity of the soils in a given permeameter drifted with time. Thus, it was necessary to pack extra permeameters and select for use only those which had conductivities in an acceptable range. For the present study, soils having mean conductivities of $1.96 \times 10^{-4} \text{ cm s}^{-1}$ + $1.51 \times 10^{-4} \text{ cm s}^{-1}$ were nominally referred to as 10^{-4} subbases, and those with mean conductivities of 4.59×10^{-6} + $1.99 \times 10^{-7} \text{ cm s}^{-1}$ were nominally referred to as 10^{-6} subbases. Soils that fell in the desired range were utilized under a series of liners, since a major element of the experimental design was to vary the flaw size and shape while holding the soil conductivity constant at only two levels. To be sure that conductivities did not drift outside the desired range, the soil conductivity was measured periodically in the absence of a FML. Since the conductivity did change somewhat with time, the soil conductivity value used for a particular instance to calculate the resistance to flow

through a defect in a FML was determined by interpolating between measurements made without the liners in place when that was necessary.

The effect of this phenomena was to yield a set of data which could not be directly compared due to variability in subbase conductivity and variability in the exact head at which the data were taken. Thus, the permeameter data were smoothed via the calculational procedure and calculated values of leakage rate at selected liquid heads were compared.

Estimating the Vertical Gap Between the FML and the Subbase

Before the calculation procedure described in Appendix A could be used, it was necessary to know the magnitude of the vertical gap between the FML and subbase. Since this cannot be directly measured, the following indirect approach was used. Values ranging from 0.001 to 0.100 cm were assumed for the gap width and using Equations 55 through 59, the flow rate was calculated for subbases having conductivities of 10^{-4} and 10^{-6} cm s⁻¹. These flow rates were then divided by the flow that would have occurred in the absence of a liner, Q_0 . The results are given in Table 9 and Figure 12.

For both soils, the fractional flow rate approached 1.0 as the gap width increased, indicating that the entire soil surface under the liner was wetted.

From these results, it is evident that the calculational procedure is capable of analyzing flow conditions that are intermediate between the situation where the liner and the subbase are in intimate contact, leaving no gap between them to allow any lateral flow (Figure 13a) and the condition where the gap between the subbase and the liner is large enough to allow liquid to freely flow in the lateral direction with

TABLE 9. CALCULATED FLOW THROUGH A LINER WITH A
0.3175 CM DIAMETER FLAW AT DIFFERENT
ASSUMED GAP WIDTHS DIVIDED BY THE FLOW
THROUGH THE SAME SUBBASE WITHOUT ANY LINER

Gap (cm)	10^{-4} Subbase	10^{-6} Subbase
0.001	0.00127	0.30912
0.002	0.00605	0.77829
0.005	0.05871	0.98194
0.007	0.13732	0.99326
0.010	0.30913	0.99760
0.020	0.77829	0.99959
0.050	0.98194	0.99986
0.070	0.99326	0.99987
0.100	0.99760	0.99987

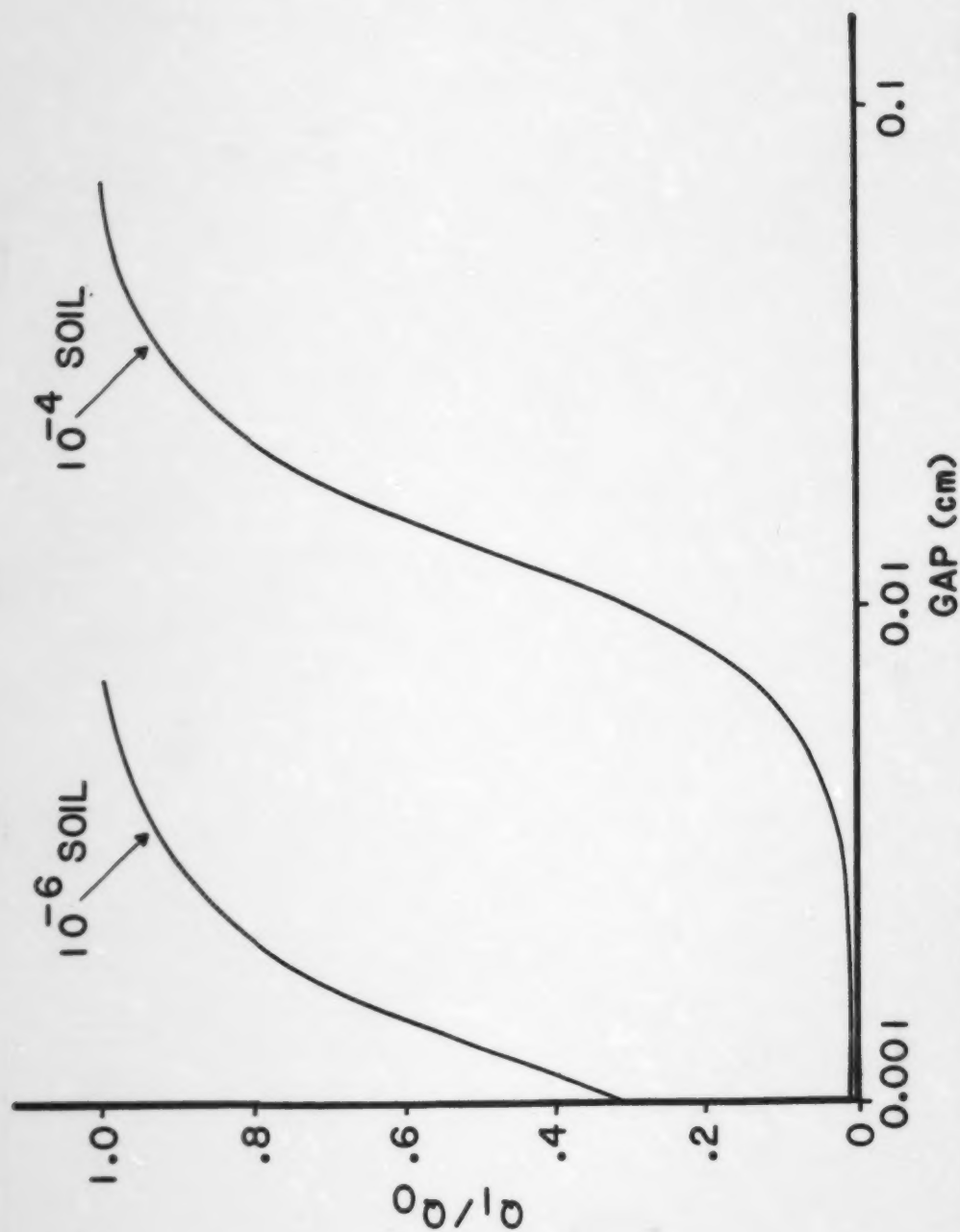


Figure 12. Flow rate divided by flow rate in the absence of a liner as the gap size changes.

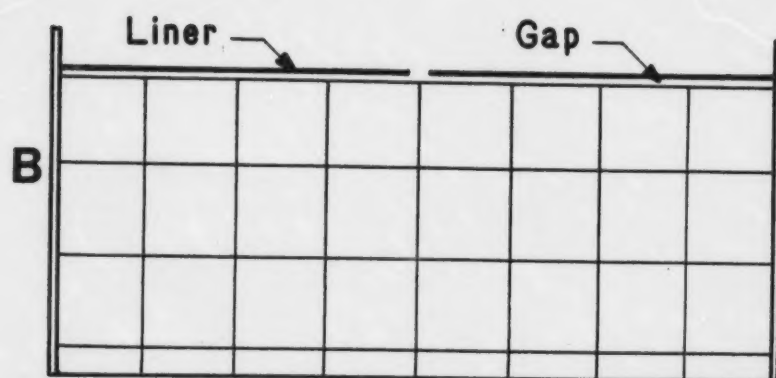
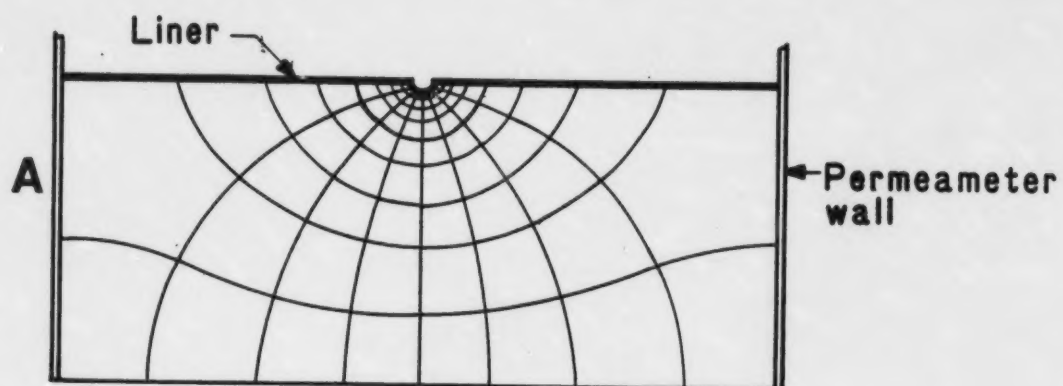


Figure 13. Flow patterns under the extreme conditions.

minimal head gradient (Figure 13b). The results (Figure 12) showed that the calculational procedure can be used to analyze all flow situations between these two extreme conditions by specifying different values of the gap width.

The calculated flow rates were compared with the observed values. From this comparison, it was possible to estimate the magnitude of the existing liner-subbase gap width. The results indicated that the actual gap depended on the grain size of the subbase. For the 10^{-4} subbase, a vertical gap of 0.01 to 0.02 cm yielded flow rates that closely agreed with the observed values, while the 10^{-6} subbase, the best agreement was found for a gap width of 0.001 to 0.002 cm. Although some relationship between the gap width and the grain size of the subbase can be expected, further investigation is recommended to verify these observations.

The above estimates for the gap width were determined from permeameter tests with only the gravel layer and liquid head providing overburden pressure. Since the overburden pressure can be expected to have a pronounced influence on the vertical gap between the liner and subbase, this was further investigated and the resulting data are presented in a later section of this report.

A comparison of calculated flow rates to the observed flow rates through an 0.08 cm HDPE liner with various sized round holes over 10^{-4} and 10^{-6} subbases at a 75 cm head are given in Table 10. In calculating these and all following results, a liner-subbase gap of 0.015 cm and 0.002 cm were assumed for the two subbases having 10^{-4} cm s⁻¹ and 10^{-6} cm s⁻¹, respectively. For all hole sizes above both subbases, a one-way analysis of variance indicated that the observed flow rate did not differ significantly from the calculated flow rate. As expected, both the observed and calculated flow rates increased as the hole diameter increased. Thus, the calculational procedure was able to accurately estimate the permeameter data.

Due to the large number of variables involved in this study, specific experiments were conducted using a limited number of permeameters to elucidate the effect of each of the variables on the leakage rate. The major controlling factors were identified and the data were then extrapolated to field conditions to provide guidance to permit writers and reviewers. Therefore, the following discussion of the data will be in the following order: the effects of FML type and thickness, geotextile, overburden pressure, permeants other than water, flaw size and head of permeant, flaw shape, and extrapolation to field conditions.

The calculations were then repeated removing the boundary conditions imposed by the permeameter wall so that flow rates under field conditions can be estimated.

TABLE 10. MEAN OBSERVED AND CALCULATED FLOW RATES THROUGH A 0.08 CM HDPE LINER WITH VARIOUS SIZED ROUND HOLES OVER 10^{-4} AND 10^{-6} SUBBASES AT 75 CM HEAD

Subbase	Flaw Diameter N		Mean Q	S.D.	Mean Q	S.D.
			Observed cm s ⁻¹		Calculated cm s ⁻¹	
10^{-4}	0.08	3	0.988a*	0.108	0.955a	0.022
	0.16	6	1.649a	0.636	1.596a	0.363
	0.64	21	1.581a	0.815	1.970a	0.626
	1.27	3	2.820a	0.857	2.129a	0.931
10^{-6}	0.08	3	0.00283a	0.000482	0.00296a	0.00106
	0.16	9	0.00451a	0.00152	0.00395a	0.00053
	0.64	23	0.00420a	0.00111	0.00407a	0.00071
	1.27	9	0.00288a	0.00085	0.00343a	0.00055

* Means in a given row followed by the same letter do not differ significantly at P = 0.05.

The Effects of FML Type and Thickness

To evaluate the effects of the type and thickness of FML on the potential leak rate, the gap width between the liner and the underlying subbase was calculated for all measurements of flow through round holes in various materials, as previously described above. The materials are listed in order of decreasing thickness and increasing flexibility (Table 11). It is apparent from the results using the 10^{-4} subbase, which had the greatest sand content, that the gap width generally decreased as one goes from thicker more rigid HDPE to the thinner less rigid hypalon, EPDM, and PVC.

Gap width over the 10^{-6} soil, which contained more clay, was an order of magnitude less than that over the 10^{-4} soil and did not show any dependence on FML material or thickness.

When the more rigid plastic overlays the sandy soil, it appears that the plastic does not deform to the shape of the soil surface, thus decreasing the gap, as much as a thinner more flexible material does. This suggests that the leak rates over soils with larger grain size may be expected to be greater for more rigid material than for more flexible materials. It must be cautioned, however, that the deformation of plastics over soil grains could lead to decreased FML thickness and eventual failure at the point of contact.

The grain size of the 10^{-6} soil was much smaller, and both the soil and plastics may possibly deform to cause a smaller gap between the

TABLE 11. AVERAGE CALCULATED GAP WIDTH BETWEEN THE SOIL AND FMLs
MADE OF DIFFERENT PLASTICS OVERLYING SAND WITH
CONDUCTIVITIES OF 10^{-4} AND 10^{-6}

			Soil Conductivity				
			10^{-4}		10^{-6}		
FML	FML						
Material	Thickness	N	Mean	Gap $\pm$ S.D	N	Mean	Gap $\pm$ S.D.
			(cm)			(cm)	
HDPE	0.25	49	0.0173	$\pm$ 0.00679	7	0.00193	$\pm$ 0.000609
HDPE	0.20	22	0.0139	$\pm$ 0.00743	3	0.00183	$\pm$ 0.000500
HDPE	0.08	42	0.0179	$\pm$ 0.0165	12	0.00197	$\pm$ 0.000708
CSPE	0.11	13	0.0128	$\pm$ 0.00277	3	0.00190	$\pm$ 0.000163
CSPE	0.09	48	0.0082	$\pm$ 0.00241	11	0.00190	$\pm$ 0.000400
EDPM	0.08	12	0.0085	$\pm$ 0.00119	2	0.00150	$\pm$ 0.000200
PVC	0.08	8	0.0083	$\pm$ 0.00331	2	0.00200	$\pm$ 0.000100
PVC	0.05	22	0.0079	$\pm$ 0.00345	3	0.00190	$\pm$ 0.000163

FML and the soil. This could lead to a decreased leak rate over soils containing more clay, both because of lower conductivity and decreased gap width.

Effect of Geotextile Under the Liner

Geotextiles may be used under FMLs to provide a protective cushion. Since the geotextiles are porous, the addition of the permeable fabric below the liner could conceivably decrease the resistance to lateral flow, thus allowing greater leak rates through equivalent size punctures in a given FML. The influence of a geotextile can best be ascertained by evaluating the thickness of the gap between the soil and the FML with and without the geotextile. This was done for all the data collected on the 10^{-4} and 10^{-6} soils for 0.08 cm HDPE liners with a 0.64 cm hole. The frequency distribution of gap widths is shown in Figures 14 to 16. For both soils, fewer runs were made with the geotextile than without; thus, the number of data points for comparisons differ. For the 10^{-4} soil, the gap width without the geotextiles averaged 0.0124 ± 0.0059 cm, while that with the geotextiles averaged 0.0101 ± 0.0048 . This suggests that the gap width with the geotextiles was slightly but not significantly less than without. Therefore, contrary to the original supposition, the geotextile does not appear to increase the flow. The expected lateral conductivity of the geotextile was lowered when it was compressed by the overburden pressure resulting from the gravel and water.

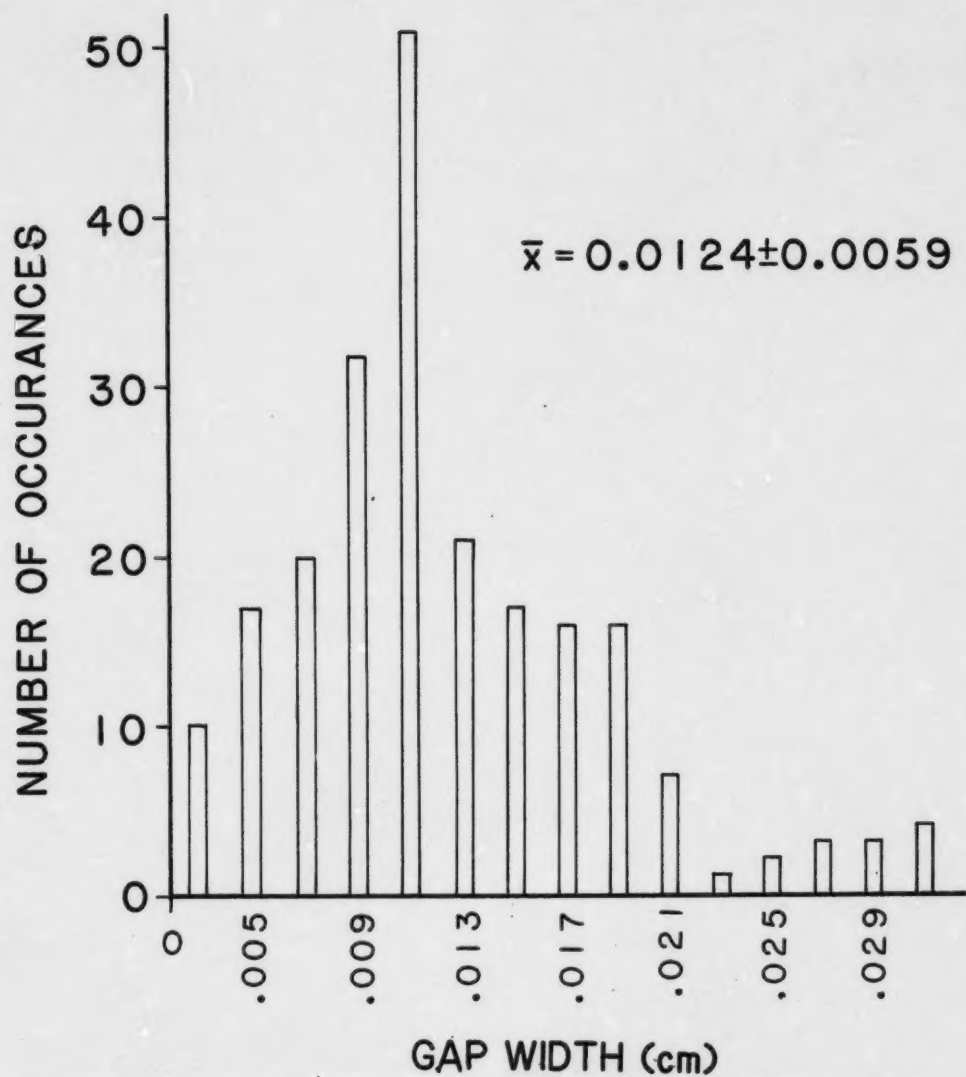


Figure 14. Frequency of various sized gap widths between 10^{-4} subbase and FML without a geotextile.

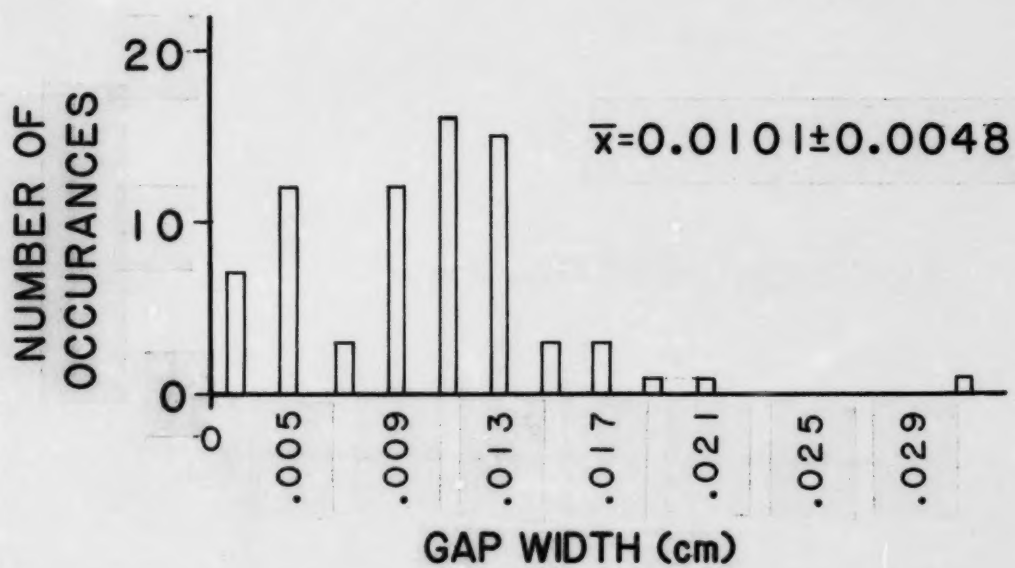


Figure 15. Frequency of various sized gap widths between 10^{-4} subbase and FML with a geotextile between.

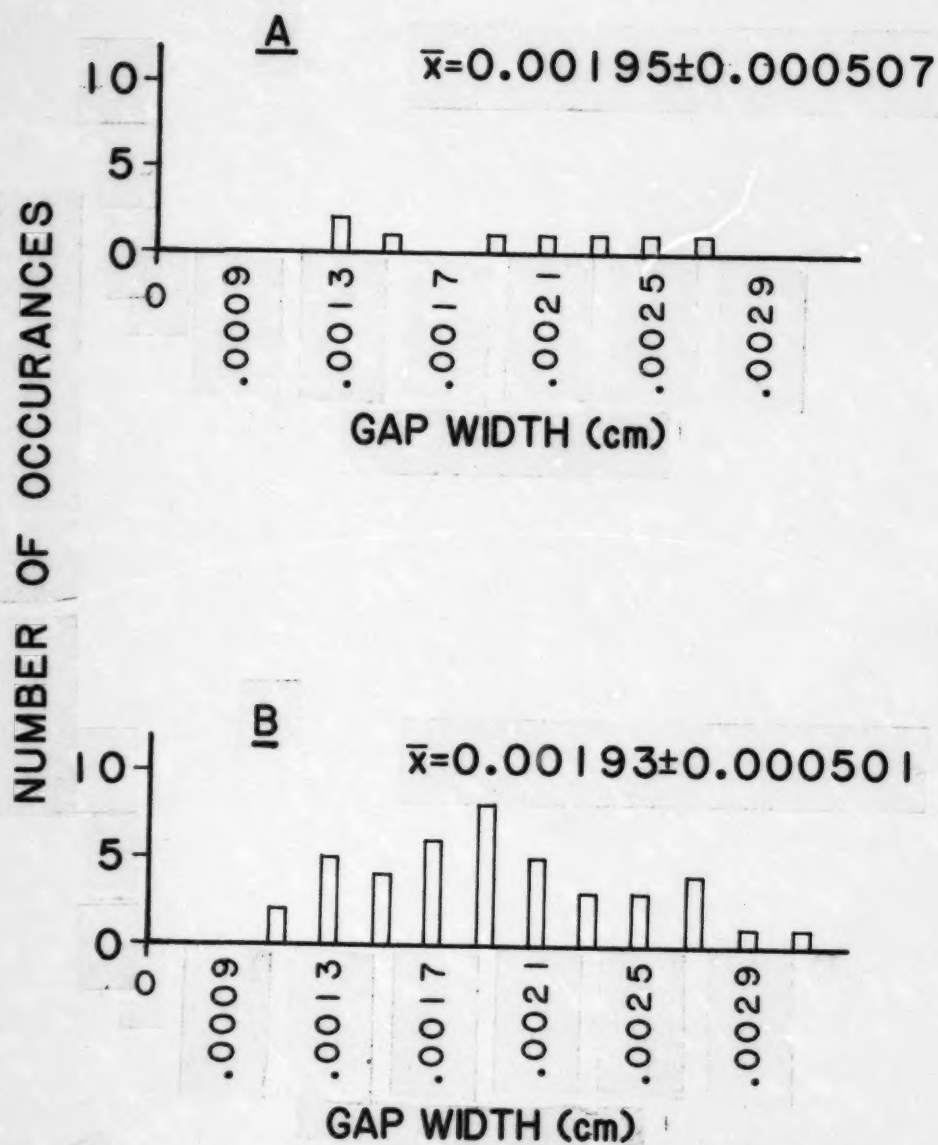


Figure 16. Frequency of various size gap widths between 10^{-6} subbase and a FML (a) in the presence of a geotextile and (b) in the absence of a geotextile.

For the 10^{-6} soil, only 10 tests were run with the geotextile, while 40 tests were run without the geotextile. Without the geotextile, the gap width averaged 0.00193 ± 0.000501 cm, while that with the geotextile averaged 0.00195 ± 0.000507 . The results were very nearly identical and did not differ significantly.

The presence of an underlying geotextile appears to have little or no effect on the rates at which liquids leak through flaws in FMLs. The use of geotextiles below FMLs may be desirable if it can be demonstrated that the use of geotextile decreases the probability of flaws in FMLs by protecting them from damage resulting from underlying aggregates.

Effect of Overburden Pressure

Three tests were conducted on 0.08 cm HDPE liners with one 0.64 cm hole in the center. For two of the three tests, the soil conductivity was determined without the liner in position immediately before and after the test conducted with the overburden. The overburden was equivalent to 15.9 Mg m^{-2} , which would simulate a 15.9 m deep layer of liquid or approximately a 16 m thick layer of waste having a density of 0.998 g cm^{-3} (Peirce, 1984). The flow rates and calculated gap widths for the runs with overburden are given in Table 12. The flow rates under overburden averaged $0.0092 \text{ cm}^3 \text{ s}^{-1}$, which is a factor of 100 less than the typical flow rate for soils of these conductivities at similar heads. The gap width between the FML and underlying soil averaged 0.0015 cm, which was a factor of 10 less than that normally occurring for the same conditions without overburden. Thus, the pressure resulting from the overburden appears to have decreased the flow rates through the holes in the liners by pressing the FML against the soil and decreasing the gap width.

Some of the decreased flow rate could possibly result from a decreased conductivity of the soil when it was subjected to the overburden. While it was not possible to evaluate this directly, a comparison of the conductivity of the soil before and after the over-

TABLE 12. HEADS, FLOW RATES, AND GAP WIDTHS FOR 10^{-4} SOILS WITH 30 MIL HDPE LINER WITH A 0.64 CM HOLE UNDER 15.9 MG M^{-2} OVERBURDEN PRESSURE

Run	Head	Flow Rate ($\text{cm}^3 \text{ s}^{-1}$)	Gap (cm)
1	79	$0.0125 \pm .0077$	.0015
2	83	$0.0114 \pm .0059$	.0015
3	-	$0.0036 \pm .00188$	.0014
Average		0.0092	.0015

burden pressure runs may help evaluate this possibility. The conductivities for the two runs for which data is available is given in Table 13. The results indicate that the conductivity was greater after the soil was subjected to overburden pressure than it was before the test. This result was unexpected and, in the least, suggests that the decreased conductivity was more likely due to the decreased gap between the FML and the soil rather than changes in the soil conductivity.

TABLE 13. CONDUCTIVITY OF SUBBASE SOIL BEFORE AND AFTER TESTING WITH OVERBURDEN PRESSURE

Run	Conductivity (cm sec ⁻¹)			
	Before		After	
	Mean	S.D.	Mean	S.D.
2	4.219x10 ⁻⁴	1.746x10 ⁻⁴	8.156x10 ⁻⁴	ID*
3	2.087x10 ⁻⁶	0.483x10 ⁻⁶	4.824x10 ⁻⁶	1.681x10 ⁻⁴

* Insufficient data.

Effects of Permeants Other Than Water

Landfill Leachate--

Synthetic landfill leachate prepared according to the formula of Ham *et al.* (1979) was substituted for water in three permeameters having a 10⁻⁴ subbase and a 0.08 cm HDPE liner with a 0.64 cm round hole. The leachate density and viscosity differed only slightly from that of water. Thus, differences in flow would likely not be influenced by these small differences in density and viscosity. Anticipated flow rates with water as the permeant were calculated by the procedure outlined above for the experimental conditions. The observed and calculated values of flow rate for two permeameters are given in Table 14. The third data set could not be analyzed due to insufficient data. The measured flow averaged six times less than the calculated water flow. The exact cause for this large decrease is not known but could include the following:

1. Interactions between chemical constituents of the leachate and the FML, possibly causing the FML to become softer and, thus, decreasing the gap width.
2. Interactions between chemical constituents of the leachate and the subbase soil to reduce the hydraulic conductivity of the subbase.

TABLE 14. OBSERVED AND CALCULATED FLOW RATES FOR
SYNTHETIC LANDFILL LEACHATE THROUGH A
0.64 CM DIAMETER HOLE IN A 0.08 CM HDPE
LINER OVER A 10^{-4} SUBBASE

Rep.	Head (cm)	Observed ----- $\text{cm}^3 \text{ s}^{-1}$ -----	Calculated -----
1	75.0	0.239	1.653
	71.7	0.275	1.586
	68.8	0.280	1.529
	66.6	0.214	1.485
2	73.5	0.285	1.623
	70.0	0.272	1.553
	66.6	0.220	1.485

These are only speculations, however, and a more thorough investigation would be required to determine the exact cause for the decreased flow rate.

Xylene--

A spent paint solvent waste was substituted for water as the permeant for two permeameters having a 10^{-4} subbase and a 0.08 cm HDPE liner with a 0.64 cm diameter round hole. The xylene waste had a density of 0.868 g cm^{-3} and a viscosity of 0.93 centistokes. The anticipated flow rate was calculated for the experimental set up utilizing these densities and viscosities. The observed and calculated flow rates are given in Table 15. The xylene flow averaged 30 and 52 times slower than predicted, even when the different density and viscosity of xylene is taken into account. Two mechanisms may have caused these observations. First, Haxo (1980) has demonstrated that HDPE absorbs xylene, thus, becoming softer, and exhibiting swelling. Softening could reduce the gap width, and the swelling could reduce the hole diameter. In addition, the subbase soil was initially saturated with water from a previous conductivity check. Thus, the soil pores were wet with water, and the immiscible xylene which floats on the water had to force its way through the large pores. Pores initially filled with water were either closed to xylene flow or the xylene had to push the water out in front of it. The xylene would have been expected to increase the conductivity of the compacted soil (Brown *et al.*, 1984), but it may be that since it was only flowing through a small hole in the liner, and since the liner was exposed to the xylene waste for only a short time, that the impact of the xylene on the clay was not observed.

TABLE 15. OBSERVED AND CALCULATED FLOW RATES FOR
XYLENE THROUGH A 0.64 CM DIAMETER HOLE
IN A 0.08 CM HDPE LINER OVER A 10^{-4}
SUBBASE

Rep.	Head (cm)	Observed ----- $\text{cm}^3 \text{ s}^{-1}$ -----	Calculated -----
1	78.3	0.204	1.289
	73.0	0.037	1.223
	70.0	0.030	1.185
	69.3	0.014	1.177
2	75.0	0.092	1.510
	72.5	0.053	1.473
	68.1	0.053	1.401
	65.5	0.028	1.351

Effect of Flaw Size and Head

The smoothed data for leakage through various sized round holes in 0.08 cm HDPE over subbases having conductivities which averaged 3.4×10^{-4} and $3.4 \times 10^{-6} \text{ cm s}^{-1}$ are shown in Figures 17 and 18, respectively. From these data, it is obvious that an increase in either flaw size or head will result in increased flow through the round flaws. Flow rates from the 0.08 cm diameter round hole in the liner over the $3.4 \times 10^{-4} \text{ cm s}^{-1}$ subbase increased gradually with head to the maximum. For the 0.16, 0.64, and 1.27 cm diameter flaws, flow rates increased steadily until an inflection point at a flow rate of $1 \text{ cm}^3 \text{ s}^{-1}$ after which the slope of the line decreased. These inflection points were 18, 21, and 30 cm head for the 1.27, 0.64, and 0.16 cm diameter flaws, respectively. These changes in slope represent the point at which the entire permeameter surface is wetted and flow at higher heads is limited due to the permeameter walls. When the conductivity of the subbase is lower, as in the case of the 3.4×10^{-6} subbase (Figure 18), more of the liquid which flows through the flaw moves laterally and thus the effects of the permeameter walls are more pronounced and the inflection points occur at much lower heads.

The decrease in flow rate due to permeameter walls was greater in the FMLs over the less permeable subbase. This is because the head loss through a hole over a permeable subbase is the controlling factor, while head loss through the same size hole over a much less permeable subbase is small and the subbase conductivity is the controlling factor.

Effect of Flaw Shape

A series of tests were conducted over the 10^{-4} subbase to

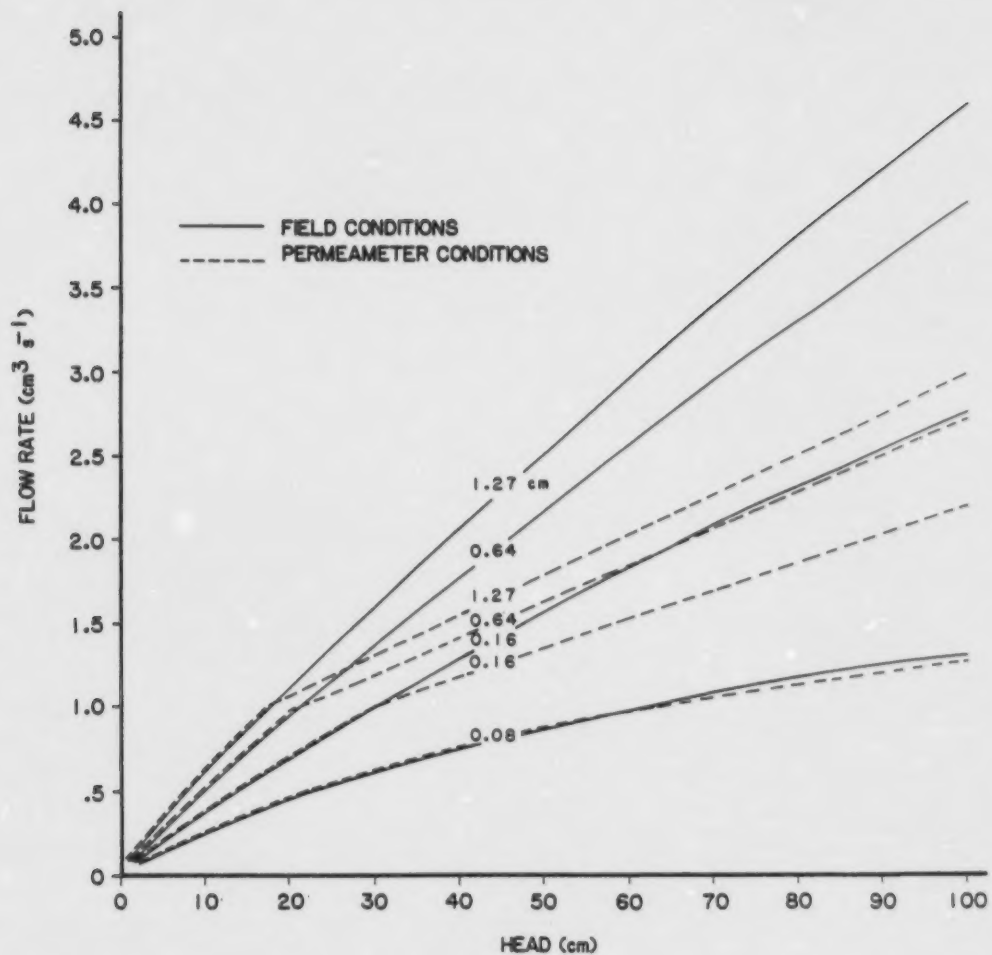


Figure 17. Calculated flow rates from various diameter round holes over 3.4×10^{-4} subbase as a function of head with and without the confining permeameter walls.

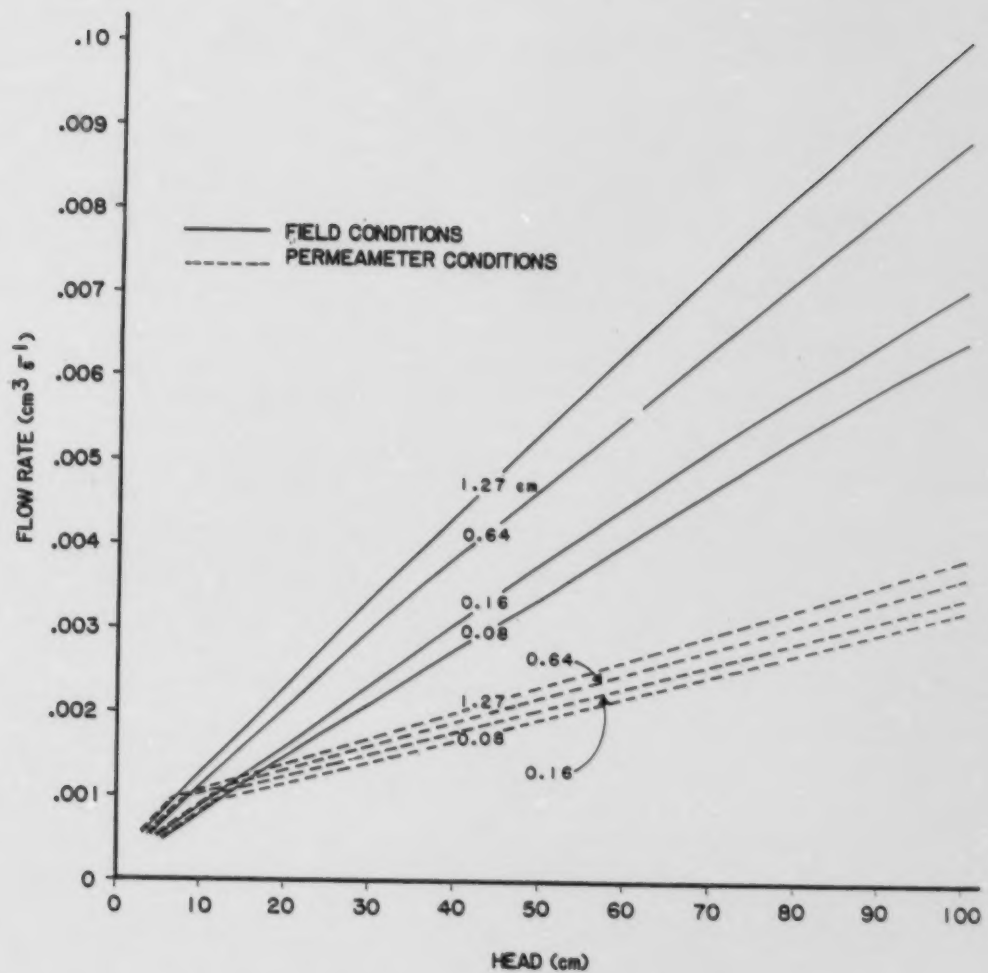


Figure 18. Calculated flow rates from various diameter round holes over 3.4×10^{-6} subbase as a function of head with and without the confining permeameter walls.

determine the influence of slit and seam failures on the leakage rates. Because of the variability of the data, it was not practical to attempt a thorough analytical interpretation. Instead, the data were used to calculate the equivalent size round hole that would be required to allow the same flow. Of necessity, this comparison was done with the data as collected, and no attempt was made to project flaws that are not constrained by the permeameter walls. The results are given in Table 16. Despite the scattered data, it is evident that the 5 cm long slits generally allowed much less water to flow through the liner than the 15 cm slits. The median 5 cm slit allowed the same amount of water to flow as would flow through a 0.08 cm diameter hole, while the median 15 cm slit was equivalent to a 2.54 cm hole. The large increase in flow with increase in slit length likely occurred because the increased slit length can allow misalignment of the material on either side of the slit liner, thus causing a greater cross-section of area for flow to occur.

TABLE 16. DISTRIBUTION OF MEASUREMENTS OF FLOW THROUGH SLITS AND SEAM FAILURES MATCHING HOLES OF THE SPECIFIED DIAMETERS. (THE TABLE INCLUDES ALL MEASUREMENTS TAKEN OVER SOILS WITH CONDUCTIVITY OF 10^{-4})

Diameter	5 cm slit	15 cm slit	5 cm seam	15 cm seam
0.02	7		3	
0.04			9	5
0.08	10	1	3	7
0.16	3	1		3
0.32		1		
0.64				
0.95		1		3
1.27		2		
1.59				1
1.91	1	1		1
2.22	1			1
2.54		2		
5.08				
7.62	1	8	14	9
Total	23	18	29	30
R_{50} (cm)	0.08	2.54	0.08	0.95

A similar relationship can be seen for the seam flaws, although it appears that many of the 5 cm seams were equivalent to 7.5 cm or larger holes, indicating large flow rates. Visual observation indicated that all seam failures "puckered" to some extent, and it may be possible that

the 5 cm length had greater strength to bridge the unseamed area, particularly when the thicker, less flexible FMLs were used. As the seam flaw gets longer, the overburden pressure may have been more effective in decreasing the gap through which water flowed, thus resulting in fewer very large leaks with the 15 cm flaws than with the 5 cm flaws. Like the 5 cm slit, the median 5 cm seam flaw allowed flow rates equivalent to those through 0.08 cm holes, while the medium 15 cm seam flaw allowed flow equivalent to that from a 0.95 cm diameter hole.

On the less permeable 10^{-6} subbase, the flow of water through slits and seams was primarily controlled by the low conductivity of the soil, as was the flow through any of the tested flaws. Since many of the measurements were taken at almost the same head, a direct comparison between conductivities for the different flaws may be made. The conductivity data and associated heads are shown in Table 17. In the

TABLE 17. AVERAGE MEASURED CONDUCTIVITY OF 0.08 CM HDPE WITH VARIOUS FLAW SIZES AND SHAPES OVER 10^{-6} SUBBASE

Flaw (cm)	N	Head (cm)	S.D.	Conductivity cm s ⁻¹	S.D
Round Hole					
Radius					
0.2	3	103.4	1.186	3.997×10^{-7}	0.891×10^{-7}
0.4	9	103.5	0.752	6.203×10^{-7}	1.738×10^{-7}
1.6	23	101.4	1.488	5.253×10^{-7}	1.771×10^{-7}
3.2	9	102.1	0.995	4.026×10^{-7}	0.995×10^{-7}
Slit Length					
5.1	6	102.5	0.852	5.645×10^{-7}	1.911×10^{-7}
15.2	6	102.3	1.176	4.553×10^{-7}	0.963×10^{-7}
Seam					
5.1	6	103.1	0.969	5.515×10^{-7}	1.617×10^{-7}
15.2	6	102.5	1.037	4.810×10^{-7}	0.978×10^{-7}

permeameters, the flow was controlled by the soil and was nearly independent of flaw size or shape. It must be cautioned, however, that under field conditions where the flow is not restricted by the permeameter walls, the flows would be expected to be greater than those reported here. The flow rates would be expected to depend on flaw size and may also depend on flaw shape.

Extrapolation To Field Conditions

The results obtained from calculations of flow rate and wetted area using a range of hole sizes in 0.08 cm HDPE under the field conditions are given for four subbase conductivities, i.e., 1.0×10^{-4} , 1.0×10^{-5} , 1.0×10^{-6} , and 1.0×10^{-7} cm s⁻¹ (Appendix D and Figures 19 through 22). The liner-soil gap widths for the 10^{-5} and 10^{-6} subbases were determined by assuming a linear relationship between the logarithm of conductivity and logarithm of gap width. The estimated gap widths were 0.015, 0.008, 0.004, and 0.002 cm for the 10^{-4} , 10^{-5} , 10^{-6} , and 10^{-7} subbases, respectively.

For the most permeable subbase (Figure 19), the flow rates ranged from 0 to 4.5 cm³ s⁻¹, and the radius of wetted area ranged from 35 to 66 cm for hole sizes from 0.08 to 1.27 cm in diameter at a head of 100 cm. When the subbase conductivity was one order of magnitude less (Figure 20), the radius of wetted area increased to 62 to 79 cm, and the maximum flow rate for the 1.27 cm hole at a 100 cm head decreased from 4.5 to 0.68 cm³ s⁻¹. A reduction in subbase conductivity to 10^{-6} again caused about an order of magnitude drop in maximum flow rate through the 1.27 cm hole at a head of 100 cm to 0.082 cm³ s⁻¹ (Figure 21). There was a corresponding increase in the radius of wetted area to 70 to 87.5 cm. The maximum flow through the 1.27 cm hole above a 10^{-7} subbase was 0.01 cm³ s⁻¹ with a radius of wetted area ranging from 77.5 to 97 cm (Figure 22). Thus, a less permeable subbase will generally result in lower flow rates and larger wetted areas from any given flow. Round holes of diameters 0.08, 0.16, 0.64, and 1.27 cm at a 100 cm head resulted in flow rates of 0.0063 to 1.4, 0.007 to 2.75, 0.0088 to 4.0, and 0.01 to 4.6 cm³ s⁻¹, respectively. The range in radius of wetted area for the 0.08, 0.16, 0.64, and 1.27 cm holes at a 100 cm head were 35 to 77.5, 52 to 82, 62 to 91, and 66 to 97 cm, respectively.

Application

The data from this study indicate that flaw size and the conductivity of the subbase are the predominant controlling parameters in determining the leakage rate through a defective FML. The type of FML material and the presence or absence of a geotextile beneath it appear to have negligible effect on the flow rate. The FML thickness had no significant effect over 10^{-6} subbase and only minor effect over the 10^{-4} subbase. Likewise, the effects of different liquid properties, i.e., viscosity and density, were small. These could easily be taken into consideration by changing the density and viscosity values used in the calculational procedure. The presence of overburden served to lower the flow rate, and a suitable reduction factor could be added to the calculational procedure if desirable.

A summary of the flow through round holes of various sizes over a range of subbase conductivities at three heads is given in Table 18.

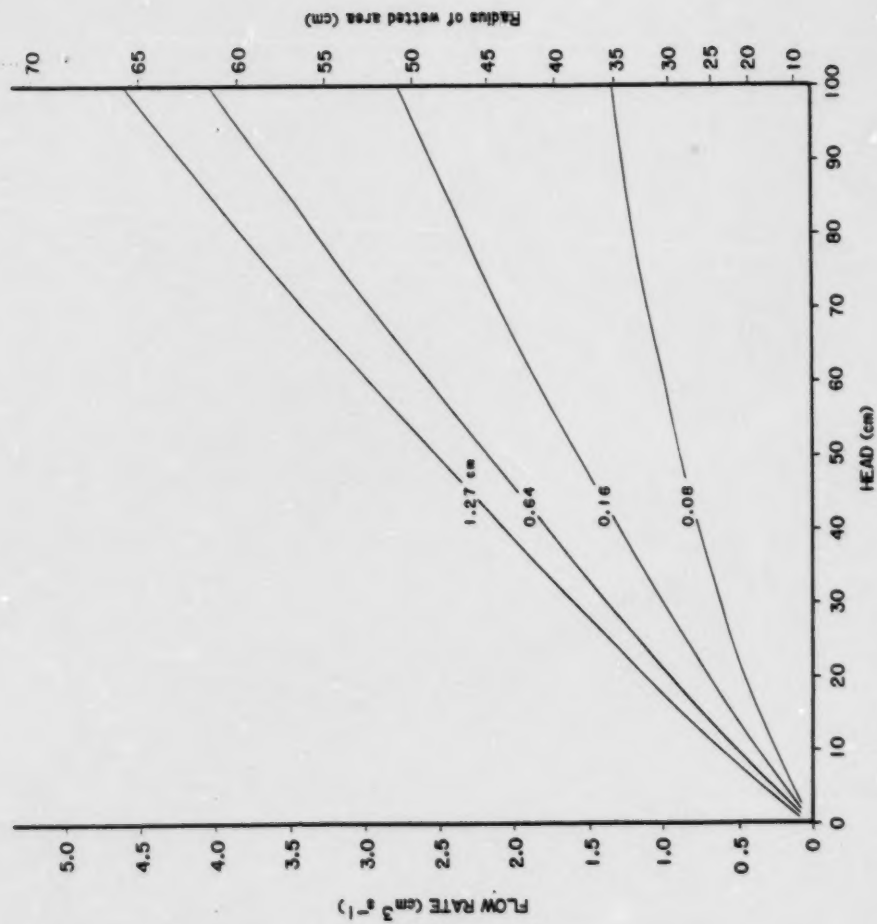


Figure 19. Calculated flow rates and radius of wetted area from various sized holes over 10^{-4} subbase as a function of head without the confining permeameter walls.

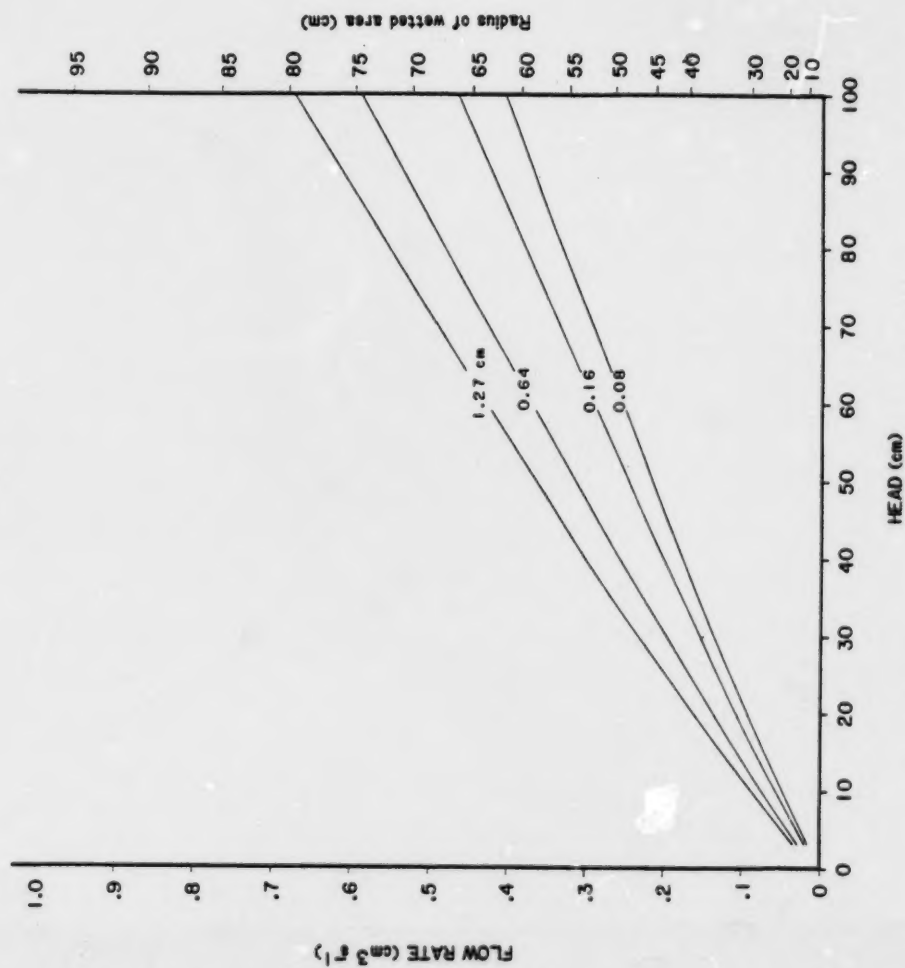


Figure 20. Calculated flow rates and radius of wetted area from various sized holes over 10-5 subbase as a function of head without the confining permeameter walls.

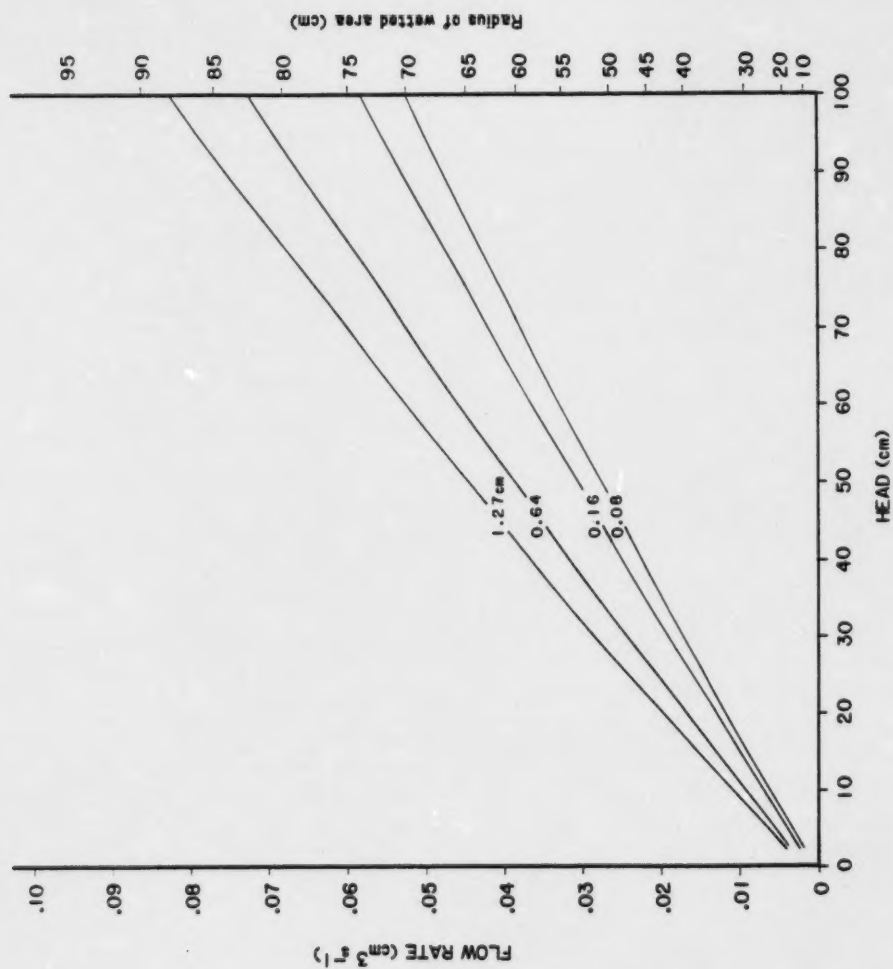


Figure 21. Calculated flow rates and radius of wetted area from various sized holes over 10^{-6} subbase as a function of head without the confining permeameter walls.

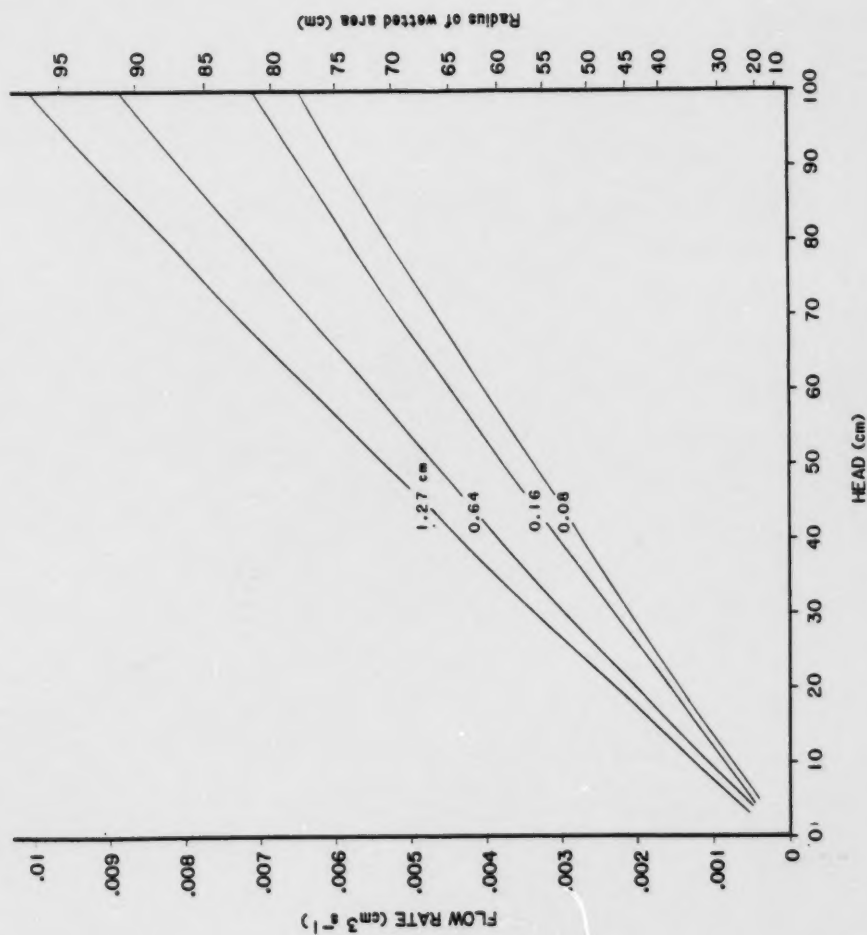


Figure 22. Calculated flow rates and radius of wetted area from various sized holes over 10^{-7} subbase as a function of head without the confining permeameter walls.

TABLE 18. CALCULATED FLOW RATES ($\text{M}^3 \text{YR}^{-1}$) FOR A RANGE OF HOLE SIZES IN FLEXIBLE MEMBRANE LINERS OVER SOILS OF DIFFERENT CONDUCTIVITIES. THE VALUES ARE GIVEN FOR THREE HEADS

K_{sat} (cm/s)	Hole diameter (cm)			
	0.08	0.16	0.64	1.27
H = 0.3 M				
3.40×10^{-4}	19.30	31.50	43.20	50.60
3.40×10^{-5}	4.30	4.38	6.28	7.30
3.40×10^{-6}	0.54	0.60	0.77	0.89
3.40×10^{-7}	0.066	0.072	0.095	0.107
H = 1.0 M				
1.30×10^{-1}		126.10	2,286.00	6,748.00
3.40×10^{-4}	42.30	87.80	128.00	147.00
3.40×10^{-5}	12.80	14.80	18.70	21.40
3.40×10^{-6}	1.66	1.83	2.29	2.61
3.40×10^{-7}	0.20	0.22	0.28	0.32
H = 10.0 M				
3.40×10^{-4}	167.0	438.0	1,030.00	1,170.00
3.40×10^{-5}	84.6	123.1	153.50	171.30
3.40×10^{-6}	14.3	15.6	18.80	21.00
3.40×10^{-7}	1.8	1.9	2.30	2.60

The radius of wetted area for the same conditions are given in Table 19. It is notable that a 1.27-cm diameter hole in a FML over a 10^{-4} subbase will leak $50.6 \text{ m}^3 \text{ yr}^{-1}$ at a head of 30 cm, but will only wet an area with a radius of 0.39 m. Potential uses for these data include the following.

1. Estimating the potential leak rate from a damaged FML under a given set of conditions. Using either Figures 17 through 20 or Tables 18 and 19 in combination with the conditions of the facility under consideration, the potential leak rate and radius of wetted area could be estimated. Such information could be of value to permit reviewers, field inspectors and facility operators.
2. Predicting the frequency of a specific size flaw in a FML under a given set of conditions that would effectively wet the entire subbase and make the influence of the FML negligible. For example, take the case of a 30 mil FML overlying a 10^{-6}

TABLE 19. CALCULATED RADIUS OF WETTED AREA (M) FOR A RANGE OF HOLE SIZES IN FLEXIBLE MEMBRANE LINERS OVER SOILS OF DIFFERENT CONDUCTIVITIES. THE VALUES ARE GIVEN FOR THREE HEADS.

K _{sat} (cm/s)	Hole diameter (cm)			
	0.08	0.16	0.64	1.27
H = 0.3 M				
3.40 x 10 ⁻⁴	0.24	0.31	0.36	0.39
3.40 x 10 ⁻⁵	0.36	0.38	0.43	0.47
3.40 x 10 ⁻⁶	0.40	0.42	0.48	0.51
3.40 x 10 ⁻⁷	0.44	0.47	0.53	0.57
H = 1.0 M				
3.40 x 10 ⁻⁴	0.36	0.51	0.62	0.66
3.40 x 10 ⁻⁵	0.62	0.66	0.75	0.80
3.40 x 10 ⁻⁶	0.70	0.74	0.82	0.88
3.40 x 10 ⁻⁷	0.78	0.82	0.91	0.97
H = 10.0 M				
3.40 x 10 ⁻⁴	0.70	1.14	1.75	1.86
3.40 x 10 ⁻⁵	1.59	1.91	2.14	2.26
3.40 x 10 ⁻⁶	2.06	2.15	2.36	2.50
3.40 x 10 ⁻⁷	2.29	2.39	2.62	2.77

subbase and containing a 1 m head of liquid. The occurrence of 0.64 cm diameter flaws at the rate of one per 2.1 m² or more frequently would make the presence of the FML superfluous. This is an important design consideration of interest to both permit writers and reviewers.

3. Aid in designing a drainage system under a liner or in the annular area between two FMLs. The ability to estimate the maximum amount of liquid expected to accumulate in the layer between two FMLs is critical to the proper design of the drainage system. Such estimates can be derived from Table 8, and should be of value to designers, permit writers, and permit reviewers.
4. For those persons involved in the design and design review of new facilities, the calculational procedure and program presented in Appendix B will be of assistance in adequately designing the initial system and in designing an adequate monitoring system.

5. The data and calculational procedure presented in Appendix E will be of use in predicting whether or not significant amounts of erosion will occur at a specific site.

It is hoped that these data will help guide those interested in designing waste retaining facilities and regulatory agencies in the proper use of FMLs and delineate conditions under which they will or will not function adequately.

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APPENDIX A

LISTING OF PERMEAMETER DATA AND DERIVATION OF THE
CALCULATIONAL PROCEDURE USED TO REDUCE THE DATA

MEASUREMENTS OF FLOW RATES OF WATER THROUGH LINERS OVER A
GRAVEL SUBBASE HAVING A CONDUCTIVITY OF 10^{-1} CM S $^{-1}$

TITLE TAG 12F HDPE 30 1/2" RND HOLE

HYD. COND. (CM/S)... = 0.130E 00

HEAD(CM)	FLOW(CC/S)
97.622	136.170
82.472	136.079
67.322	136.170
52.172	136.079

TITLE TAG 12H HDPE 30 1/2" RND HOLE

HYD. COND. (CM/S)... = 0.130E 00

HEAD(CM)	FLOW(CC/S)
97.574	121.642
82.322	132.700
65.546	86.147
50.497	78.150

TITLE TAG 6F HDPE 30 1/4" RND HOLE

HYD. COND. (CM/S)... = 0.130E 00

HEAD(CM)	FLOW(CC/S)
96.960	70.476
80.679	68.372
64.398	54.106
50.229	43.872

TITLE TAG 20H HDPE 30 6" VERT SLIT

HYD. COND. (CM/S)... = 0.130E 00

HEAD(CM)	FLOW(CC/S)
97.015	35.510
80.644	30.776
64.273	25.411
49.744	21.596

TITLE TAG 20H HDPE 30 6" VERT SLIT

HYD. COND. (CM/S)... = 0.130E 00

HEAD(CM)	FLOW(CC/S)
96.952	83.239
80.656	74.240
64.359	59.200
50.406	49.423

TITLE TAG 10H HDPE 30 1/2" RND HOLE

HYD. COND. (CM/S)... = 0.130E 00

HEAD(CM)	FLOW(CC/S)
97.383	149.586
82.370	146.304
66.892	112.272
51.155	103.636

TITLE TAG 5H HDPE 30 1/4" RND HOLE

HYD. COND. (CM/S)... = 0.130E 00

HEAD(CM)	FLOW(CC/S)
96.997	66.966
80.591	63.922
64.185	52.085
50.291	41.515

TITLE TAG 10F HDPE 30 1/2" RND HOLE

HYD. COND. (CM/S)... = 0.130E 00

HEAD(CM)	FLOW(CC/S)
97.687	110.100
83.061	96.888
68.434	73.400
55.911	69.033

TITLE TAG 27H HDPE 30 6" SEAM SLIT

HYD. COND. (CM/S)... = 0.130E 00

HEAD(CM)	FLOW(CC/S)
96.904	40.886
80.711	31.017
64.519	20.599
51.261	13.336

TITLE TAG 25F HDPE 30 6" SEAM SLIT

HYD. COND. (CM/S)... = 0.130E 00

HEAD(CM)	FLOW(CC/S)
97.013	106.102
81.040	94.733
65.066	75.787
50.890	62.294

TITLE TAG 15F HDPE 30 1/16" RND HOLE

HYD. COND. (CM/S)... = 0.130E 00

HEAD(CM)	FLOW(CC/S)
96.903	197.535
80.690	154.173
64.476	105.352
49.935	77.191

TITLE TAG 5F HDPE 30 1/4" RND HOLE

HYD. COND. (CM/S)... = 0.130E 00

HEAD(CM)	FLOW(CC/S)
97.013	63.283
80.840	63.283
64.666	49.723
50.540	47.265

TITLE TAG 14H HDPE 30 1/16" RND HOLE

HYD. COND. (CM/S)... = 0.130E 00

HEAD(CM)	FLOW(CC/S)
98.872	4.574
86.615	4.128
74.359	3.526
63.915	3.311

TITLE TAG 14F HDPE 30 1/16" RND HOLE

HYD. COND. (CM/S)... = 0.130E 00

HEAD(CM)	FLOW(CC/S)
96.915	5.153
80.546	4.627
64.177	3.779
49.496	3.050

TITLE TAG 25F HDPE 30 6" SEAM SLIT

HYD. COND. (CM/S)... = 0.130E 00

HEAD(CM)	FLOW(CC/S)
97.287	49.991
81.260	43.069
65.234	35.891
51.010	29.721

TITLE TAG 11H HDPE 30 1/2" RND HOLE

HYD. COND. (CM/S)... = 0.130E 00

HEAD(CM)	FLOW(CC/S)
97.120	156.577
80.960	139.179
64.799	121.936
50.710	102.479

TITLE TAG 11F HDPE 30 1/2" RND HOLE

HYD. COND. (CM/S)... = 0.130E 00

HEAD(CM)	FLOW(CC/S)
97.193	170.705
81.180	136.564
65.167	130.061
50.930	111.857

TITLE TAG 13F HDPE 30 1/16" RND HOLE

HYD. COND. (CM/S)... = 0.130E 00

HEAD(CM)	FLOW(CC/S)
97.017	4.288
80.850	3.611
64.683	3.027
51.750	2.628

TITLE TAG 13H HDPE 30 1/16" RND HOLE

HYD. COND. (CM/S)... = 0.130E 00

HEAD(CM)	FLOW(CC/S)
97.017	4.188
80.851	3.554
64.684	3.007
49.251	2.318

TITLE TAG 4F HDPE 30 1/4" RND HOLE

HYD. COND. (CM/S)... = 0.130E 00

HEAD(CM)	FLOW(CC/S)
96.907	40.961
80.721	38.116
64.535	31.911
52.421	26.737

TITLE TAG 4H HDPE 30 1/4" RND HOLE

HYD. COND. (CM/S)... = 0.130E 00

HEAD(CM)	FLOW(CC/S)
96.819	43.789
80.458	34.327
64.097	26.789
51.008	22.770

TITLE TAG 6H HDPE 30 1/4" RND HOLE

HYD. COND. (CM/S)... = 0.130E 00

HEAD(CM)	FLOW(CC/S)
96.769	45.315
80.506	36.742
64.243	28.924
49.556	24.910

TITLE TAG 26H HDPE 30 6" SEAM SLIT HOECHST

HYD. COND. (CM/S)... = 0.130E 00

HEAD(CM)	FLOW(CC/S)
99.896	25.558
89.689	22.512
79.481	22.629
69.273	18.489
59.066	16.396
49.981	15.763

TITLE TAG 26F HDPE 30 6" SEAM SLIT FOSS

HYD. COND. (CM/S)... = 0.130E 00

HEAD(CM)	FLOW(CC/S)
99.846	73.726
89.539	58.980
79.232	58.980
68.925	46.563
58.618	42.129
49.032	35.225

TITLE TAG 19H HDPE 30 6"VERT SLIT HOECHST

HYD. COND. (CM/S)... = 0.130E 00

HEAD(CM)	FLOW(CC/S)
100.126	131.539
89.978	131.539
79.831	131.539
69.683	100.589
59.535	95.001
48.931	88.757

TITLE TAG 21F HDPE 30 6" VERT. SLIT FOSS

HYD. COND. (CM/S)... = 0.130E 00

HEAD(CM)	FLOW(CC/S)
100.122	139.381
89.966	128.659
79.810	128.659
69.654	98.387
59.497	88.030
48.910	82.488

TITLE TAG 21H HDPE 30 6" VERT SLIT HOECHST

HYD. COND. (CM/S)... = 0.130E 00

HEAD(CM)	FLOW(CC/S)
100.108	71.483
89.923	57.186
79.738	41.844
69.553	32.370
59.368	29.579
49.438	26.718

TITLE TAG 19F HDPE 30 6" VERT SLIT FOSS

HYD. COND. (CM/S)... = 0.130E 00

HEAD(CM)	FLOW(CC/S)
100.125	100.321
89.974	91.783
79.823	86.276
69.672	71.897
59.522	61.626
49.523	53.992

TAG:30 LINER:PVC 30 1/4" ROUND HOLE

HYD. COND. (CM/S)..... = 0.130E 00

HEAD(CM)	FLOW(CC/S)
78.422	39.761
67.945	31.808
55.880	35.343
43.980	30.890
33.185	29.193
23.177	26.507

TAG:31 LINER:PVC 30 1/4" ROUND HOLE

HYD. COND. (CM/S).....= 0.130E 00

HEAD(CM)	FLOW(CC/S)
71.755	7.017
61.912	5.941

TAG:32 LINER:PVC 30 1/4" ROUND HOLE

HYD. COND. (CM/S).....= 0.130E 00

HEAD(CM)	FLOW(CC/S)
66.992	46.387
51.117	36.146
35.242	31.991

TAG:33 LINER:PVC 30 1/4" ROUND HOLE

HYD. COND. (CM/S).....= 0.130E 00

HEAD(CM)	FLOW(CC/S)
70.802	37.668
53.340	32.269
32.220	23.745

TAG:34 LINER:PVC 20 1/4" ROUND HOLE

HYD. COND. (CM/S).....= 0.130E 00

HEAD(CM)	FLOW(CC/S)
76.835	15.346
54.292	14.594
31.115	9.495

TAG:35 LINER:PVC 20 1/4" ROUND HOLE

HYD. COND. (CM/S).....= 0.130E 00

HEAD(CM)	FLOW(CC/S)
71.006	34.170
56.401	51.954
36.195	28.356

TAG:36 LINER:HYPALON 36 1/4" ROUND HOLE

HYD. COND. (CM/S).....= 0.130E 00

HEAD(CM)	FLOW(CC/S)
77.470	16.312
70.485	21.829
56.832	38.435
44.767	9.175
32.067	19.565

TAG:37 LINER:HYPALON 36 1/4" ROUND HOLE

HYD. COND. (CM/S).....= 0.130E 00

HEAD(CM)	FLOW(CC/S)
74.295	24.740
53.975	21.206
32.385	16.632

TAG:38 LINER:HYPALON 36 1/4" ROUND HOLE

HYD. COND. (CM/S).....= 0.130E 00

HEAD(CM)	FLOW(CC/S)
62.230	42.411
32.385	28.356
16.510	6.237

TAG:39 LINER:HYPALON 45 1/4" ROUND HOLE

HYD. COND. (CM/S).....= 0.130E 00

HEAD(CM)	FLOW(CC/S)
66.675	31.077
45.085	26.507
27.140	22.109

TAG:40 LINER:HYPALON 45 1/4" ROUND HOLE

HYD. COND. (CM/S).....= 0.130E 00

HEAD(CM)	FLOW(CC/S)
96.400	1.391
80.350	1.120
65.600	1.036
52.250	0.925

TAG:39 LINER:HYPALON 45 1/4" ROUND HOLE

HYD. COND. (CM/S).....= 0.130E 00

HEAD(CM)	FLOW(CC/S)
98.100	0.798
83.100	0.735
67.200	0.630
52.200	0.500

TAG:40 LINER:HYPALON 45 1/4" ROUND HOLE

HYD. COND. (CM/S).....= 0.130E 00

HEAD(CM)	FLOW(CC/S)
97.200	1.542
82.200	1.374
67.950	1.216
52.950	1.016

TAG:41 LINER:HYPALON 45 1/4" ROUND HOLE

HYD. COND. (CM/S).....= 0.130E 00

HEAD(CM)	FLOW(CC/S)
65.087	96.561
39.052	58.694
22.225	34.303

TAG:41 LINER:HYPALON 45 1/4" ROUND HOLE

HYD. COND. (CM/S).....= 0.130E 00

HEAD(CM)	FLOW(CC/S)
97.050	1.449
82.050	1.189
65.600	1.080
50.600	0.862

TAG:42 LINER:EPDM 30 1/4" ROUND HOLE

HYD. COND. (CM/S).....= 0.130E 00

HEAD(CM)	FLOW(CC/S)
93.450	1.105
79.150	0.995
65.150	0.733
51.500	0.676

TAG:43 LINER:EPDM 30 1/4" ROUND HOLE

HYD. COND. (CM/S).....= 0.130E 00

HEAD(CM)	FLOW(CC/S)
66.040	79.521
48.895	35.343
32.702	103.377
19.050	17.671

TAG:44 LINER:EPDM 30 1/4" ROUND HOLE

HYD. COND. (CM/S).....= 0.130E 00

HEAD(CM)	FLOW(CC/S)
72.390	97.192
59.372	71.948
48.260	60.587
35.560	53.014
24.447	48.596

TAG:45 LINER:HDPE 80 1/4" ROUND HOLE

HYD. COND. (CM/S).....= 0.130E 00

HEAD(CM)	FLOW(CC/S)
66.675	151.469
46.355	90.881
32.385	88.357
22.225	63.617

TAG:45 LINER:HDPE 80 1/4" ROUND HOLE

HYD. COND. (CM/S).....= 0.130E 00

HEAD(CM)	FLOW(CC/S)
98.400	1.722
83.400	1.678
66.450	0.913
51.450	2.819

TAG:46 LINER:HDPE 80 1/4" ROUND HOLE

HYD. COND. (CM/S).....= 0.130E 00

HEAD(CM)	FLOW(CC/S)
73.977	100.727
59.372	143.138
38.100	62.369

TAG:46 LIN:HDPE 80 1/4" ROUND HOLE

HYD. COND. (CM/S).....= 0.130E 00

HEAD(CM)	FLOW(CC/S)
96.650	1.779
81.650	1.590
65.800	1.384
50.800	1.071

TAG:47 LINER:HDPE 80 1/4" ROUND HOLE

HYD. COND. (CM/S).....= 0.130E 00

HEAD(CM)	FLOW(CC/S)
72.390	60.587
56.515	90.124
32.461	61.496

TAG:47 LINER:HDPE 80 1/4" ROUND HOLE

HYD. COND. (CM/S).....= 0.130E 00

HEAD(CM)	FLOW(CC/S)
97.300	1.743
82.300	1.523
66.850	1.352
51.850	1.070

TAG:48 LINER:HDPE 100 1/4" ROUND HOLE

HYD. COND. (CM/S).....= 0.130E 00

HEAD(CM)	FLOW(CC/S)
70.485	172.296
46.990	115.667
24.765	36.447

TAG:49 LINER:HDPE 100 1/4" ROUND HOLE

HYD. COND. (CM/S).....= 0.130E 00

HEAD(CM)	FLOW(CC/S)
73.660	74.220
53.022	67.593
32.474	24.245

TAG:50 LINER:HDPE 100 1/4" ROUND HOLE

HYD. COND. (CM/S).....= 0.130E 00

HEAD(CM)	FLOW(CC/S)
74.930	106.028
57.467	77.312
44.132	37.110
30.797	61.850
18.097	33.134

TAG:60 LINER:HYPALON 45 1/16" ROUND HOLE

HYD. COND. (CM/S).....= 0.130E 00

HEAD(CM)	FLOW(CC/S)
96.350	3.474
83.500	3.053
69.400	3.214
54.000	2.656

TAG:61 LINER:HYPALON 45 1/16" ROUND HOLE

HYD. COND. (CM/S).....= 0.130E 00

HEAD(CM)	FLOW(CC/S)
99.250	2.646
89.050	2.509
68.950	2.773
49.900	1.777

TAG:62/17 LINER:HYPALON 45 1/16" ROUND HOLE

HYD. COND. (CM/S).....= 0.130E 00

HEAD(CM)	FLOW(CC/S)
88.100	3.167
61.400	2.154

TAG:63/17 LINER:EPDM 30 1/16" ROUND HOLE

HYD. COND. (CM/S).....= 0.130E 00

HEAD(CM)	FLOW(CC/S)
91.700	1.957
71.050	1.396
56.450	0.893
48.800	0.862

TAG:64/26 LINER:EPDM 30 1/16" ROUND HOLE

HYD. COND. (CM/S).....= 0.130E 00

HEAD(CM)	FLOW(CC/S)
90.100	3.550
72.450	2.979
56.700	2.351

TAG:65 LINER:EPDM 30 1/16" ROUND HOLE

HYD. COND. (CM/S).....= 0.130E 00

HEAD(CM)	FLOW(CC/S)
93.200	4.483
77.200	3.731
62.700	3.822
50.750	2.600

TAG:69 LINER:HDPE 100 1/16" ROUND HOLE

HYD. COND. (CM/S).....= 0.130E 00

HEAD(CM)	FLOW(CC/S)
95.200	5.716
79.950	5.109
65.550	4.403
52.050	3.457

TAG:70 LINER:HDPE 100 1/16" ROUND HOLE

HYD. COND. (CM/S).....= 0.130E 00

HEAD(CM)	FLOW(CC/S)
94.700	2.771
78.500	2.324
65.000	1.918
54.200	1.587

TAG:71 LINER:HDPE 100 1/16" ROUND HOLE

HYD. COND. (CM/S).....= 0.130E 00

HEAD(CM)	FLOW(CC/S)
95.650	4.822
80.750	4.203
66.550	3.374
53.050	2.776

TAG:90 LINER:HDPE 100 1/2" ROUND HOLE

HYD. COND. (CM/S).....= 0.130E 00

HEAD(CM)	FLOW(CC/S)
97.500	4.040
82.500	4.040
67.500	3.578
52.500	2.566

TAG:91 LINER:HDPE 100 1/2" ROUND HOLE

HYD. COND. (CM/S).....= 0.130E 00

HEAD(CM)	FLOW(CC/S)
97.500	3.422
82.500	4.289
67.500	2.699
52.500	3.131

TAG:92 LINER:HDPE 100 1/2" ROUND HOLE

HYD. COND. (CM/S).....= 0.130E 00

HEAD(CM)	FLOW(CC/S)
97.500	3.348
82.500	3.538
67.500	2.833
52.500	2.372

TAG:2 LINER:HDPE 30 1/4" ROUND HOLE

HYD. COND. (CM/S).....= 0.130E 00

HEAD(CM)	FLOW(CC/S)
95.150	1.217
80.150	1.145
66.950	0.988
51.950	0.845

TAG:3 LINER:HDPE 100 1/4" ROUND HOLE

HYD. COND. (CM/S).....= 0.130E 00

HEAD(CM)	FLOW(CC/S)
97.100	1.256
82.100	1.068
68.700	1.068
55.200	0.810

TAG:4 LINER:HDPE 30 1/4" ROUND HOLE

HYD. COND. (CM/S).....= 0.130E 00

HEAD(CM)	FLOW(CC/S)
98.000	0.962
81.300	0.731
65.450	0.942
51.650	0.589

TAG:4" LINER:HDPE 30 1/4" ROUND HOLE

HYD. COND. (CM/S).....= 0.130E 00

HEAD(CM)	FLOW(CC/S)
96.200	1.299
81.200	1.183
65.550	1.026
50.550	0.878

TAG:5 LINER:HDPE 30 1/4" ROUND HOLE

HYD. COND. (CM/S).....= 0.130E 00

HEAD(CM)	FLOW(CC/S)
96.500	1.713
88.500	0.900
77.800	1.134
67.400	1.138
61.800	0.948
55.850	0.914
49.400	0.796

TAG:6 LINER:HDPE 30 1/4" ROUND HOLE

HYD. COND. (CM/S).....= 0.130E 00

HEAD(CM)	FLOW(CC/S)
101.950	1.023
94.300	1.002
87.500	1.051
79.900	0.972
71.600	0.802
63.950	0.823
55.650	0.677
48.050	0.969

TAG:10 LINER:HDPE 30 1/2" ROUND HOLE

HYD. COND. (CM/S).....= 0.130E 00

HEAD(CM)	FLOW(CC/S)
98.100	3.498
90.650	2.615
81.450	2.535
73.250	3.069
64.900	2.056
52.800	2.038

TAG:10' LINER:HDPE 30 1/2" ROUND HOLE

HYD. COND. (CM/S).....= 0.130E 00

HEAD(CM)	FLOW(CC/S)
98.200	3.330
83.200	3.299
67.200	2.634
52.200	2.368

TAG:11 LINER:HDPE 30 1/2" ROUND HOLE

HYD. COND. (CM/S).....= 0.130E 00

HEAD(CM)	FLOW(CC/S)
97.550	2.935
90.100	2.933
83.950	2.521
75.050	2.597
62.300	2.168
50.900	1.919

TAG:11' LINER:HDPE 30 1/2" ROUND HOLE

HYD. COND. (CM/S).....= 0.130E 00

HEAD(CM)	FLOW(CC/S)
97.050	3.837
82.050	3.325
65.600	2.860
50.600	2.390

TAG:12 LINER:HDPE 30 1/2" ROUND HOLE

HYD. COND. (CM/S).....= 0.130E 00

HEAD(CM)	FLOW(CC/S)
98.750	3.653
91.200	3.592
82.500	3.352
74.350	3.156
64.500	2.826
52.450	2.104

TAG:12' LINER:HDPE 30 1/2" ROUND HOLE

HYD. COND. (CM/S).....= 0.130E 00

HEAD(CM)	FLOW(CC/S)
96.800	3.628
81.800	3.962
67.000	2.852
52.000	2.868

TAG:13 LINER:HDPE 30 1/16" ROUND HOLE

HYD. COND. (CM/S).....= 0.130E 00

HEAD(CM)	FLOW(CC/S)
89.300	4.442
71.800	3.676
62.600	3.319
55.500	2.905

TAG:14 LINER:HDPE 30 1/16" ROUND HOLE

HYD. COND. (CM/S).....= 0.130E 00

HEAD(CM)	FLOW(CC/S)
100.950	2.040
96.050	2.166
86.100	5.320
74.500	4.964
65.700	2.533
56.350	2.375

TAG:15 LINER:HDPE 30 1/16" ROUND HOLE

HYD. COND. (CM/S).....= 0.130E 00

HEAD(CM)	FLOW(CC/S)
95.625	4.405
77.050	3.757
57.705	2.861

TAG:99 LINER:HYPALON 36 2" VERTICAL SLIT

HYD. COND. (CM/S).....= 0.130E 00

HEAD(CM)	FLOW(CC/S)
83.250	5.808
75.750	3.456
67.750	6.903
58.050	3.840
49.800	3.479

TAG:100 LINER:HYPALON 36 2" VERTICAL SLIT

HYD. COND. (CM/S).....= 0.130E 00

HEAD(CM)	FLOW(CC/S)
99.150	27.751
87.450	24.123
75.150	21.113
62.400	17.370

TAG:101 LINER:HYPALON 36 2" VERTICAL SLIT

HYD. COND. (CM/S).....= 0.130E 00

HEAD(CM)	FLOW(CC/S)
98.200	0.407
81.850	0.352
66.500	0.279
55.950	0.222

TAG:120 LINER:HYPALON 36 6" VERTICAL SLIT

HYD. COND. (CM/S).....= 0.130E 00

HEAD(CM)	FLOW(CC/S)
97.450	3.774
82.400	3.683
67.350	3.867
52.300	3.749

TAG:121 LINER:HYPALON 36 6" VERTICAL SLIT

HYD. COND. (CM/S).....= 0.130E 00

HEAD(CM)	FLOW(CC/S)
97.400	147.220
81.650	145.962
65.900	145.595
50.150	148.948

TAG:122 LINER:HYPALON 36 6" VERTICAL SLIT

HYD. COND. (CM/S).....= 0.130E 00

HEAD(CM)	FLOW(CC/S)
97.550	2.186
82.150	2.485
66.750	2.411
51.300	2.350

TAG:162 LINER:HYPALON 36 6" VERTICAL SLIT

HYD. COND. (CM/S).....= 0.130E 00

HEAD(CM)	FLOW(CC/S)
95.200	5.383
80.800	4.244
75.500	4.145
67.500	3.465
55.700	2.825
48.550	2.461

TAG:163 LINER:HYPALON 36 6" SEAM SLIT

HYD. COND. (CM/S).....= 0.130E 00

HEAD(CM)	FLOW(CC/S)
98.950	4.634
87.800	3.755
76.350	3.007
66.800	2.458
60.850	2.005

TAG:78 LINER:HYPALON 36 1/2" ROUND HOLE

HYD. COND. (CM/S).....= 0.130E 00

HEAD(CM)	FLOW(CC/S)
101.350	4.049
92.800	4.499
77.300	3.903
61.800	3.092
51.100	3.590

TAG:79 LINER:HYPALON 36 1/2" ROUND HOLE

HYD. COND. (CM/S).....= 0.130E 00

HEAD(CM)	FLOW(CC/S)
101.400	4.417
92.800	4.616
80.600	4.419
66.400	3.470
52.350	3.226

TAG:80 LINER:HYPALON 36 1/2" ROUND HOLE

HYD. COND. (CM/S).....= 0.130E 00

HEAD(CM)	FLOW(CC/S)
100.700	5.076
90.950	5.461
78.800	3.837
65.600	4.120
52.200	3.287

TAG:17 LINER:HDPE 30 2" VERTICAL SLIT

HYD. COND. (CM/S).....= 0.130E 00

HEAD(CM)	FLOW(CC/S)
77.787	1.205
68.580	0.657

TAG:19 LINER:HDPE 30 6" VERTICAL SLIT

HYD. COND. (CM/S).....= 0.130E 00

HEAD(CM)	FLOW(CC/S)
76.200	106.028
69.850	212.056
62.230	212.056
58.420	106.028
53.340	159.042

TAG:20 LINER:HDPE 30 6" VERTICAL SLIT

HYD. COND. (CM/S).....= 0.130E 00

HEAD(CM)	FLOW(CC/S)
80.493	65.737
77.000	56.460
71.755	42.411
65.087	34.459

TAG:21 LINER:HDPE 30 6" VERTICAL SLIT

HYD. COND. (CM/S).....= 0.130E 00

HEAD(CM)	FLOW(CC/S)
75.565	132.535
67.945	371.098
58.420	212.056
48.260	212.056
39.370	159.042
31.750	159.042
24.130	159.042

TAG:22 LINER:HDPE 30 2" SEAM SLIT

HYD. COND. (CM/S).....= 0.130E 00

HEAD(CM)	FLOW(CC/S)
58.420	8.156
33.972	4.802

TAG:23 LINER:HDPE 30 2" SEAM SLIT

HYD. COND. (CM/S).....= 0.130E 00

HEAD(CM)	FLOW(CC/S)
73.508	7.526
52.553	5.355
26.035	5.049

TAG:24 LINER:HDPE 30 2" SEAM SLIT

HYD. COND. (CM/S).....= 0.130E 00

HEAD(CM)	FLOW(CC/S)
80.645	15.147
78.422	15.904

TAG:25 LINER:HDPE 30 6" SEAM SLIT

HYD. COND. (CM/S).....= 0.130E 00

HEAD(CM)	FLOW(CC/S)
57.150	122.340
31.750	66.268

TAG:26 LINER:HDPE 30 6" SEAM SLIT

HYD. COND. (CM/S).....= 0.130E 00

HEAD(CM)	FLOW(CC/S)
58.420	93.794
32.067	98.076

TAG:27 LINER:HDPE 30 6" SEAM SLIT

HYD. COND. (CM/S).....= 0.130E 00

HEAD(CM)	FLOW(CC/S)
68.110	322.679
51.117	225.310
39.370	176.713
25.400	212.056

MEASUREMENTS OF FLOW RATES OF WATER THROUGH LINERS OVER A
SAND SUBBASE HAVING A CONDUCTIVITY OF 10^{-4} CM S $^{-1}$

TAG:7/3 LINER:HDPE 30 1/4" ROUND HOLE

HYD. COND.(CM/S)... = 0.120E-03

HEAD(CM)	FLOW(CC/S)
96.300	0.812
91.150	0.765
87.900	0.742
84.850	0.673
81.550	0.858

TAG:9/2 LINER:HDPE 30 1/4" ROUND HOLE

HYD. COND.(CM/S)... = 0.323E-03

HEAD(CM)	FLOW(CC/S)
100.300	1.291
91.750	1.236
84.200	1.077
77.650	0.939
70.800	0.893

TAG:10/8 LINER:HDPE 30 1/2" ROUND HOLE

HYD. COND.(CM/S)... = 0.583E-03

HEAD(CM)	FLOW(CC/S)
98.700	3.790
82.900	3.664
67.600	3.120
52.800	2.288

TAG:11/3 LINER:HDPE 30 1/2" ROUND HOLE

HYD. COND.(CM/S)... = 0.153E-03

HEAD(CM)	FLOW(CC/S)
95.100	2.289
80.000	1.807
67.050	1.324

TAG:12/2 LINER:HDPE 30 1/2" ROUND HOLE

HYD. COND.(CM/S)... = 0.323E-03

HEAD(CM)	FLOW(CC/S)
97.350	2.435
82.500	2.319
63.950	1.398

TAG:13/22 LINER:HDPE 30 1/16" ROUND HOLE

HYD. COND.(CM/S)... = 0.546E-03

HEAD(CM)	FLOW(CC/S)
100.100	1.164
91.600	0.895
85.000	0.703
80.700	0.582

TAG:14/21 LINER:HDPE 30 1/16" ROUND HOLE

HYD. COND.(CM/S)... = 0.343E-03

HEAD(CM)	FLOW(CC/S)
98.450	1.682
82.500	1.697
68.950	1.279

TAG:15/2 LINER:HDPE 30 1/16" ROUND HOLE

HYD. COND.(CM/S)... = 0.306E-03

HEAD(CM)	FLOW(CC/S)
99.900	1.307
94.350	1.284
88.950	1.242
83.000	1.120

TAG:32/22 LINER:PVC 30 1/4" ROUND HOLE

HYD. COND.(CM/S)... = 0.546E-03

HEAD(CM)	FLOW(CC/S)
103.700	0.215
102.050	0.229
100.400	0.227
98.750	0.165

TAG 37/21 LINER:PVC 30 1/4" ROUND HOLE

HYD. COND.(CM/S)... = 0.458E-03

HEAD(CM)	FLOW(CC/S)
103.650	1.796
96.500	1.504
89.550	1.397
84.950	1.273

TAG:33/23 LINER:PVC 20 1/4" ROUND HOLE

HYD. COND.(CM/S)... = 0.210E-03

HEAD(CM)	FLOW(CC/S)
105.050	0.197
103.400	0.186
101.900	0.162
100.900	0.083

TAG:33/2 LINER:PVC 20 1/4" ROUND HOLE

HYD. COND.(CM/S)... = 0.160E-03

HEAD(CM)	FLOW(CC/S)
99.500	1.255
95.450	0.983
92.050	0.826
88.700	0.718

TAG:34/1 LINER:PVC 20 1/4" ROUND HOLE

HYD. COND.(CM/S)... = 0.136E-03

HEAD(CM)	FLOW(CC/S)
104.450	0.058
103.950	0.058
103.350	0.081
102.750	0.058
102.450	0.028

TAG:34/21 LINER:PVC 20 1/4" ROUND HOLE

HYD. COND.(CM/S)... = 0.299E-03

HEAD(CM)	FLOW(CC/S)
105.950	0.776
103.050	1.261
100.250	1.174
97.750	1.000
95.550	0.913
92.950	0.899

TAG:35/21 LINER:PVC 20 1/4" ROUND HOLE

HYD. COND.(CM/S)... = 0.343E-03

HEAD(CM)	FLOW(CC/S)
103.900	1.197
95.400	0.974
87.550	0.846
80.400	3.247

TAG:36/2 LINER:HYPALON 36 1/4" ROUND HOLE

HYD. COND.(CM/S)... = 0.323E-03

HEAD(CM)	FLOW(CC/S)
101.400	1.118
92.950	1.077
85.200	0.935
77.950	0.807

TAG:37/19 LINER:HYPALON 36 1/4" ROUND HOLE

HYD. COND.(CM/S)... = 0.340E-03

HEAD(CM)	FLOW(CC/S)
102.750	0.870
95.550	0.800
89.100	0.696
83.100	0.938

TAG:38/23 LINER:HYPALON 36 1/4" ROUND HOLE

HYD. COND.(CM/S)... = 0.441E-03

HEAD(CM)	FLOW(CC/S)
105.350	0.580
102.700	0.649
100.050	0.580
97.550	0.580
95.500	0.557

TAG:39/1 LINER:HYPALON 45 1/4" ROUND HOLE

HYD. COND.(CM/S)... = 0.136E-03

HEAD(CM)	FLOW(CC/S)
101.150	1.345
98.000	1.577
94.700	1.484
91.850	1.191

TAG:40/3 LINER:HYPALON 45 1/4" ROUND HOLE

HYD. COND.(CM/S)... = 0.153E-03

HEAD(CM)	FLOW(CC/S)
97.000	0.966
90.100	0.835
85.650	0.651

TAG:40/19 LINER:HYPALON 45 1/4" ROUND HOLE

HYD. COND.(CM/S)... = 0.382E-03

HEAD(CM)	FLOW(CC/S)
101.550	2.421
93.250	2.004
85.450	1.590
79.650	1.514

TAG:41/22 LINER:HYPALON 45 1/4" ROUND HOLE

HYD. COND.(CM/S)... = 0.546E-03

HEAD(CM)	FLOW(CC/S)
101.000	1.760
93.200	1.509
86.600	1.261
81.100	1.048

TAG:42/8 LINER:EPDM 30 1/4" ROUND HOLE

HYD. COND.(CM/S)... = 0.583E-03

HEAD(CM)	FLOW(CC/S)
102.650	1.026
97.100	0.904
92.350	0.748
87.950	0.626

TAG:43/23 LINER:EPDM 30 1/4" ROUND HOLE

HYD. COND.(CM/S)... = 0.441E-03

HEAD(CM)	FLOW(CC/S)
105.250	0.580
102.750	0.580
100.450	0.487
98.100	0.426

TAG:44/21 LINER:EPDM 30 1/4" ROUND HOLE

HYD. COND.(CM/S)... = 0.343E-03

HEAD(CM)	FLOW(CC/S)
103.150	1.098
96.500	0.959
90.950	0.758
86.600	0.674

TAG:45/19 LINER:HDPE 80 1/4" ROUND HOLE

HYD. COND.(CM/S)... = 0.340E-03

HEAD(CM)	FLOW(CC/S)
105.550	0.070
105.250	0.070
104.950	0.070
104.650	0.070
104.250	0.076

TAG:45/2 LINER:HDPE 80 1/4" ROUND HOLE

HYD. COND.(CM/S)... = 0.289E-03

HEAD(CM)	FLOW(CC/S)
101.600	2.742
95.300	2.737
88.650	2.319
81.850	1.992

TAG:46/1 LINER:HDPE 80 1/4" ROUND HOLE

HYD. COND.(CM/S)... = 0.136E-03

HEAD(CM)	FLOW(CC/S)
103.000	0.881
99.300	0.835
95.750	0.812
92.000	0.723

TAG:47/2 LINER:HDPE 80 1/4" ROUND HOLE

HYD. COND.(CM/S)... = 0.323E-03

HEAD(CM)	FLOW(CC/S)
95.700	2.613
78.850	2.172
64.750	1.828
51.050	1.704

TAG:47/8 LINER:HDPE 80 1/4" ROUND HOLE

HYD. COND.(CM/S)... = 0.556E-03

HEAD(CM)	FLOW(CC/S)
103.650	2.702
95.850	2.424
89.100	2.331
83.050	2.068
77.250	1.861

TAG:48/2 LINER:HDPE 100 1/4" ROUND HOLE

HYD. COND.(CM/S)... = 0.111E-03

HEAD(CM)	FLOW(CC/S)
101.050	0.018
96.500	0.017
92.100	0.015

TAG:49/8 LINER:HDPE 100 1/4" ROUND HOLE

HYD. COND.(CM/S)...= 0.650E-04

HEAD(CM)	FLOW(CC/S)
103.050	0.013
99.650	0.013
95.500	0.011
91.550	0.009

TAG:49/19 LINER:HDPE 100 1/4" ROUND HOLE

HYD. COND.(CM/S)...= 0.525E-03

HEAD(CM)	FLOW(CC/S)
101.350	3.081
92.700	2.908
85.150	2.319
77.250	3.150
68.950	2.138

TAG:48/19 LINER:HDPE 100 1/4" ROUND HOLE

HYD. COND.(CM/S)...= 0.340E-03

HEAD(CM)	FLOW(CC/S)
102.200	2.458
91.950	2.296
79.050	1.844
62.850	3.826

TAG:50/23 LINER:HDPE 100 1/4" ROUND HOLE

HYD. COND.(CM/S)...= 0.441E-03

HEAD(CM)	FLOW(CC/S)
104.200	0.340
102.050	0.365
99.950	0.292
97.400	0.299

TAG:50/1 LINER:HDPE 100 1/4" ROUND HOLE

HYD. COND.(CM/S)...= 0.360E-04

HEAD(CM)	FLOW(CC/S)
102.250	0.007
100.200	0.009
98.250	0.008
96.450	0.007
94.600	0.007

TAG:48/3 LINER:HDPE 100 1/4" ROUND HOLE

HYD. COND.(CM/S)...= 0.235E-03

HEAD(CM)	FLOW(CC/S)
96.450	2.805
88.800	2.393
82.000	2.119
76.050	1.857
70.600	1.705

TAG:69/8 LINER:HDPE 100 1/16" ROUND HOLE

HYD. COND.(CM/S)... = 0.250E-03

HEAD(CM)	FLOW(CC/S)
103.300	0.990
95.900	1.143
88.850	1.026
82.900	0.930
78.150	0.974

TAG:70/3 LINER:HDPE 100 1/16" ROUND HOLE

HYD. COND.(CM/S)... = 0.251E-03

HEAD(CM)	FLOW(CC/S)
96.950	2.718
88.200	2.289
75.300	1.811
62.450	1.361
53.550	1.086

TAG:71/8 LINER:HDPE 100 1/16" ROUND HOLE

HYD. COND.(CM/S)... = 0.255E-03

HEAD(CM)	FLOW(CC/S)
99.950	1.968
91.700	1.746
84.350	1.610
74.900	1.530

TAG:90/1 LINER:HDPE 100 1/2" ROUND HOLE

HYD. COND.(CM/S)... = 0.134E-03

HEAD(CM)	FLOW(CC/S)
102.800	1.128
98.900	0.967
95.300	0.967
91.850	0.883
87.500	0.910

TAG:91/1 LINER:HDPE 100 1/2" ROUND HOLE

HYD. COND.(CM/S)... = 0.134E-03

HEAD(CM)	FLOW(CC/S)
101.000	0.980
92.150	0.921
84.750	0.804
78.950	0.730

TAG:92/3 LINER:HDPE 100 1/2" ROUND HOLE

HYD. COND.(CM/S)... = 0.251E-03

HEAD(CM)	FLOW(CC/S)
92.750	2.918
81.850	2.259
70.700	1.825
60.000	1.569

TAG: 192/19 LINER: HDPE 30 1/32" ROUND HOLE

HYD. COND. (CM/S) ... = 0.327E-03

HEAD(CM)	FLOW(CC/S)
104.150	1.056
100.100	0.994
95.150	1.349
91.450	0.402
88.200	0.823

TAG: 193/19 LINER: HDPE 30 1/32" ROUND HOLE

HYD. COND. (CM/S) ... = 0.327E-03

HEAD(CM)	FLOW(CC/S)
102.600	1.051
95.100	1.007
88.050	0.591
81.900	1.416
77.600	0.744

TAG: 194/2 LINER: HDPE 30 1/32" ROUND HOLE

HYD. COND. (CM/S) ... = 0.146E-03

HEAD(CM)	FLOW(CC/S)
100.000	0.851
93.850	0.852
88.050	0.846
82.950	0.784
78.350	0.740

TAG: 16/23 LINER: HDPE 30 2" VERTICAL SLIT

HYD. COND. (CM/S) ... = 0.441E-03

HEAD(CM)	FLOW(CC/S)
105.700	0.080
105.400	0.051
105.200	0.054
104.950	0.052

TAG: 17/22 LINER: HDPE 30 2" VERTICAL SLIT

HYD. COND. (CM/S) ... = 0.546E-03

HEAD(CM)	FLOW(CC/S)
104.100	0.008
103.850	0.007
103.600	0.007

TAG: 18/2 LINER: HDPE 30 2" VERTICAL SLIT

HYD. COND. (CM/S) ... = 0.289E-03

HEAD(CM)	FLOW(CC/S)
100.150	1.565
90.000	2.064
80.900	1.230

TAG:19/3 LINER:HDPE 30 6" VERTICAL SLIT

HYD. COND.(CM/S)... = 0.153E-03

HEAD(CM)	FLOW(CC/S)
95.250	3.634
82.500	2.704
68.050	2.359

TAG:20/8 LINER:HDPE 30 6" VERTICAL SLIT

HYD. COND.(CM/S)... = 0.583E-03

HEAD(CM)	FLOW(CC/S)
99.000	4.638
82.500	4.854
63.550	3.094

TAG:21/23 LINER:HDPE 30 6" VERTICAL SLIT

HYD. COND.(CM/S)... = 0.441E-03

HEAD(CM)	FLOW(CC/S)
98.700	2.672
82.500	2.602
69.850	1.783

TAG:22/1 LINER:HDPE 30 2" SEAM SLIT

HYD. COND.(CM/S)... = 0.151E-03

HEAD(CM)	FLOW(CC/S)
105.850	0.101
105.350	0.074
104.900	0.070

TAG:22/1 LINER:HDPE 30 2" SEAM SLIT

HYD. COND.(CM/S)... = 0.124E-03

HEAD(CM)	FLOW(CC/S)
102.650	1.519
97.800	1.456
92.800	1.245
89.000	1.221
86.150	1.092

TAG:23/21 LINER:HDPE 30 2" SEAM SLIT

HYD. COND.(CM/S)... = 0.343E-03

HEAD(CM)	FLOW(CC/S)
97.350	3.733
82.500	3.422
64.750	2.094

TAG:23/2 LINER:HDPE 30 2" SEAM SLIT

HYD. COND.(CM/S)... = 0.203E-03

HEAD(CM)	FLOW(CC/S)
101.450	2.137
95.950	1.872
89.500	1.732
83.600	1.565
79.100	1.391

TAG:24/19 LINER:HDPE 30 2" SEAM SLIT

HYD. COND.(CM/S)... = 0.426E-03

HEAD(CM)	FLOW(CC/S)
103.750	2.976
96.650	2.976
89.600	2.934
82.500	3.018
75.400	7.379

TAG:25/1 LINER:HDPE 30 6" SEAM SLIT

HYD. COND.(CM/S)... = 0.133E-03

HEAD(CM)	FLOW(CC/S)
102.000	0.910
98.750	0.998
95.800	0.866
92.750	0.886
89.800	0.804

TAG:26/8 LINER:HDPE 30 6" SEAM SLIT

HYD. COND.(CM/S)... = 0.407E-03

HEAD(CM)	FLOW(CC/S)
105.300	2.810
101.000	2.943
97.100	2.516
93.750	1.640

TAG:27/19 LINER:HDPE 30 6" SEAM SLIT

HYD. COND.(CM/S)... = 0.425E-03

HEAD(CM)	FLOW(CC/S)
99.500	4.035
89.100	3.200
80.450	2.818
72.150	2.957
64.900	2.087
59.500	2.000

TAG :183/2 LINER:HYPALON 36 1/32" ROUND HOLE

HYD. COND.(CM/S)... = 0.160E-03

HEAD(CM)	FLOW(CC/S)
103.300	0.000
103.050	0.000
102.750	0.000
102.450	0.000

TAG:184/21 LINER:HYPALON 36 1/32" ROUND HOLE

HYD. COND.(CM/S)... = 0.458E-03

HEAD(CM)	FLOW(CC/S)
104.100	0.006
101.350	0.006
98.800	0.006
96.400	0.006

TAG:185/21 LINER:HYPALON 36 1/16" ROUND HOLE

HYD. COND.(CM/S)... = 0.300E-03

HEAD(CM)	FLOW(CC/S)
103.250	0.006
101.750	0.007
100.100	0.008

TAG:185/21 LINER:HYPALON 36 1/32" ROUND HOLE

HYD. COND.(CM/S)... = 0.326E-03

HEAD(CM)	FLOW(CC/S)
102.950	0.010
99.550	0.009
96.050	0.010
93.250	0.010

TAG 58/19 LINER:HYPALON 36 1/16" ROUND HOLE

HYD. COND.(CM/S)... = 0.133E-03

HEAD(CM)	FLOW(CC/S)
104.450	0.008
102.050	0.008
99.450	0.007
97.600	0.007

TAG:59/3 LINER:HYPALON 36 1/16" ROUND HOLE

HYD. COND.(CM/S)... = 0.300E-03

HEAD(CM)	FLOW(CC/S)
98.650	0.000
98.400	0.001
97.850	0.002

TAG:78/1 LINER:HYPALON 36 1/2" ROUND HOLE

HYD. COND.(CM/S)... = 0.920E-04

HEAD(CM)	FLOW(CC/S)
102.800	0.002
101.650	0.002
100.500	0.002
99.700	0.001

TAG:79/3 LINER:HYPALON 36 1/2" ROUND HOLE

HYD. COND.(CM/S)...= 0.255E-03

HEAD(CM)	FLOW(CC/S)
97.350	0.024
91.250	0.023
85.400	0.020
79.600	0.015

TAG:80/8 LINER:HYPALON 36 1/2" ROUND HOLE

HYD. COND.(CM/S)...= 0.157E-03

HEAD(CM)	FLOW(CC/S)
101.900	0.016
97.200	0.015
93.150	0.014
89.600	0.013

TAG:90/8 LINER:HDPE 100 1/2" ROUND HOLE

HYD. COND.(CM/S)...= 0.650E-04

HEAD(CM)	FLOW(CC/S)
101.850	0.015
98.100	0.013
94.950	0.011
92.050	0.010
89.300	0.010

TAG:91/19 LINER:HDPE 100 1/2" ROUND HOLE

HYD. COND.(CM/S)...= 0.107E-03

HEAD(CM)	FLOW(CC/S)
100.350	0.032
94.400	0.025
89.050	0.020
84.250	0.018
79.250	0.015

TAG:92/3 LINER:HDPE 100 1/2" ROUND HOLE

HYD. COND.(CM/S)...= 0.255E-03

HEAD(CM)	FLOW(CC/S)
94.800	0.048
86.300	0.041
78.000	0.035
69.400	0.028
60.700	0.023

TAG:99/21 LINER:HYPALON 36 2" VERTICAL SLIT

HYD. COND.(CM/S)...= 0.424E-03

HEAD(CM)	FLOW(CC/S)
103.500	0.012
99.700	0.012
95.750	0.012
91.650	0.011

TAG:100/8 LINER:HYPALON 36 2" VERTICAL SLIT

HYD. COND.(CM/S)... = 0.790E-04

HEAD(CM)	FLOW(CC/S)
103.000	0.009
100.100	0.009
97.600	0.009
94.500	0.008

TAG:101/19 LINER:HYPALON 36 2" VERTICAL SLIT

HYD. COND.(CM/S)... = 0.133E-03

HEAD(CM)	FLOW(CC/S)
103.300	0.010
100.500	0.010
98.150	0.010
95.900	0.009
93.450	0.009

TAG:120/3 LINER:HYPALON 36 6" VERTICAL SLIT

HYD. COND.(CM/S)... = 0.255E-03

HEAD(CM)	FLOW(CC/S)
96.700	0.055
88.250	0.045
79.250	0.039
69.550	0.031
58.900	0.024

TAG:121/2 LINER:HYPALON 36 6" VERTICAL SLIT

HYD. COND.(CM/S)... = 0.126E-03

HEAD(CM)	FLOW(CC/S)
100.200	0.015
95.850	0.015
91.750	0.015
88.100	0.013
84.800	0.014

TAG:122/8 LINER:HYPALON 36 6" VERTICAL SLIT

HYD. COND.(CM/S)... = 0.790E-04

HEAD(CM)	FLOW(CC/S)
103.750	0.010
101.450	0.011
99.100	0.009
96.900	0.008

TAG:141/21 LINER:HYPALON 36 2" SEAM SLIT

HYD. COND.(CM/S)... = 0.424E-03

HEAD(CM)	FLOW(CC/S)
103.850	0.009
101.800	0.009
99.650	0.008
97.300	0.007

TAG:142/19 LINER:HYPALON 36 2" SEAM SLIT

HYD. COND.(CM/S)... = 0.107E-03

HEAD(CM)	FLOW(CC/S)
104.400	0.003
103.100	0.003
101.550	0.003
100.200	0.003

TAG:143/1 LINER:HYPALON 36 2" SEAM SLIT

HYD. COND.(CM/S)... = 0.430E-04

HEAD(CM)	FLOW(CC/S)
101.750	0.004
100.800	0.003
99.650	0.004
98.500	0.004

TAG:162/1 LINER: HYPALON 36 6" SEAM SLIT

HYD. COND.(CM/S)... = 0.430E-04

HEAD(CM)	FLOW(CC/S)
102.850	0.004
101.250	0.006
99.700	0.005
98.450	0.004
97.350	0.004

TAG:163/2 LINER:HYPALON 36 6" SEAM SLIT

HYD. COND.(CM/S)... = 0.111E-03

HEAD(CM)	FLOW(CC/S)
100.050	0.010
96.350	0.011
92.600	0.010
88.750	0.009
85.150	0.008

TAG:164/21 LINER:HYPALON 36 6" SEAM SLIT

HYD. COND.(CM/S)... = 0.326E-03

HEAD(CM)	FLOW(CC/S)
103.150	0.009
100.400	0.009
97.350	0.008
94.600	0.007
92.350	0.007

TAG:57/1 LINER:HYPALON 36 1/16" ROUND HOLE

HYD. COND.(CM/S)... = 0.920E-04

HEAD(CM)	FLOW(CC/S)
103.250	0.006
101.750	0.007
100.100	0.008

TAG: 27F/19 LINER: HDPE 30 6" SEAM SLIT FOSS

HYD. COND.(CM/S)... = 0.394E-04

HEAD(CM)	FLOW(CC/S)
105.283	1.228
102.490	1.145
99.697	1.027
96.904	0.941
93.664	0.530

TAG: 6H LINER: HDPE 30 1/4" ROUND HOLE HOECHST

HYD. COND.(CM/S)... = 0.400E-04

HEAD(CM)	FLOW(CC/S)
100.894	1.161
92.900	1.072
83.678	1.039
71.381	0.888
59.596	0.810
48.836	0.693

TAG: 12H/1 LINER: HDPE 30 1/2" ROUND HOLE HOECHST

HYD. COND.(CM/S)... = 0.351E-04

HEAD(CM)	FLOW(CC/S)
103.424	0.345
101.614	0.392
99.545	0.356
97.476	0.327
95.821	0.336

TAG: 25H/2 LINER: HDPE 30 6" SEAM SLIT

HYD. COND.(CM/S)... = 0.415E-04

HEAD(CM)	FLOW(CC/S)
103.698	0.563
101.094	0.537
98.089	0.448
95.585	0.448
93.642	0.404

TAG: 19F/2 LINER: HDPE 30 6" VERT. SLIT FOSS

HYD. COND.(CM/S)... = 0.434E-04

HEAD(CM)	FLOW(CC/S)
103.324	0.445
101.515	0.428
99.447	0.402
97.378	0.360
95.672	0.346

TAG 19H/21 LINER: HDPE 30 6" VERT. SLIT HOECHST

HYD. COND.(CM/S)... = 0.191E-03

HEAD(CM)	FLOW(CC/S)
102.459	2.987
95.576	2.376
87.984	2.834
80.392	1.391
73.812	1.481
67.687	1.308

TAG 20F/3 LINER: HDPE 30 6" VERT. SLIT FOSS

HYD. COND.(CM/S)... = 0.105E-03

HEAD(CM)	FLOW(CC/S)
102.462	0.912
98.581	0.903
94.497	1.154
89.391	1.295
83.264	1.165

TAG 12F/1 LINER: HDPE 30 1/2" ROUND HOLE FOSS

HYD. COND.(CM/S)... = 0.351E-04

HEAD(CM)	FLOW(CC/S)
103.979	0.370
102.415	0.315
100.329	0.598
98.244	0.359
96.451	0.355

TAG 15H/8 LINER: HDPE 30 1/16" ROUND HOLE HOECHST

HYD. COND.(CM/S)... = 0.278E-04

HEAD(CM)	FLOW(CC/S)
104.725	0.574
102.537	0.450
100.510	0.383
98.687	0.335
97.238	0.312

TAG 13H/3 LINER: HDPE 30 1/16" ROUND HOLE HOECHST

HYD. COND.(CM/S)... = 0.105E-03

HEAD(CM)	FLOW(CC/S)
104.700	0.000
104.553	0.015
104.037	0.029
102.985	0.054

TAG 14F/21 LINER: HDPE 30 1/16" ROUND HOLE FOSS

HYD. COND.(CM/S)... = 0.253E-03

HEAD(CM)	FLOW(CC/S)
107.861	0.058
106.911	0.129

TAG: 14H/21 LINER: HDPE 30 1/16" ROUND HOLE HOECHST

HYD. COND.(CM/S)... = 0.190E-03

HEAD(CM)	FLOW(CC/S)
104.300	0.007
103.987	0.013
103.637	0.008

TAG: 25F/2 LINER: HDPE 30 6" SEAM SLIT FOSS

HYD. COND.(CM/S)... = 0.402E-04

HEAD(CM)	FLOW(CC/S)
102.499	0.677
99.252	0.606
96.159	0.544
93.067	0.472
89.510	0.428

TAG: 10H/1 LINER: HDPE 30 1/2" ROUND HOLE

HYD. COND.(CM/S)... = 0.383E-04

HEAD(CM)	FLOW(CC/S)
103.536	0.346
101.761	0.328
100.037	0.328
98.262	0.310

TAG: 11F/8 LINER: HDPE 30 1/2" ROUND HOLE FOSS

HYD. COND.(CM/S)... = 0.332E-04

HEAD(CM)	FLOW(CC/S)
104.186	0.273
103.453	0.301
102.615	0.282
101.798	0.286

TAG: 6F/19 LINER: HDPE 30 1/4" ROUND HOLE FOSS

HYD. COND.(CM/S)... = 0.514E-04

HEAD(CM)	FLOW(CC/S)
105.110	0.824
102.657	0.721
99.835	0.684
96.838	0.631

TAG: 11H/8 LINER: HDPE 30 1/2" ROUND HOLE HOECHST

HYD. COND.(CM/S)... = 0.332E-04

HEAD(CM)	FLOW(CC/S)
103.705	0.335
100.966	0.379
97.876	0.354
95.096	0.340
92.830	0.283

TAG: 10F/1 LINER: HDPE 30 1/2" ROUND HOLE FOSS

HYD. COND.(CM/S)... = 0.383E-04

HEAD(CM)	FLOW(CC/S)
102.273	0.321
100.993	0.328
99.380	0.310
97.659	0.308
96.099	0.285

TAG: 7F/2 LINER: HDPE 30 1/4" ROUND HOLE FOSS

HYD. COND.(CM/S)... = 0.402E-04

HEAD(CM)	FLOW(CC/S)
100.297	0.464
97.638	0.418
95.032	0.401
92.790	0.353

TAG: 13F/3 LINER: HDPE 30 1/16" ROUND HOLE FOSS

HYD. COND.(CM/S)... = 0.105E-03

HEAD(CM)	FLOW(CC/S)
100.150	0.108
99.362	0.076
98.662	0.071

TAG: 15F/8 LINER: HDPE 30 1/16" ROUND HOLE FOSS

HYD. COND.(CM/S)... = 0.331E-04

HEAD(CM)	FLOW(CC/S)
104.530	0.463
102.251	0.435
99.910	0.407
97.939	0.352

TAG: 6H/19 LINER: HDPE 30 1/4" ROUND HOLE HOECHST

HYD. COND.(CM/S)... = 0.437E-04

HEAD(CM)	FLOW(CC/S)
104.605	0.910
100.851	0.829
96.734	0.753
92.738	0.650

TAG: 43F/19 LINER: EPDM 30 1/4" ROUND HOLE FOSS

HYD. COND.(CM/S)... = 0.271E-03

HEAD(CM)	FLOW(CC/S)
102.581	1.640
96.200	1.437
89.563	1.285
82.926	1.130
77.310	1.104
73.378	1.004

TAG: 30F/22 LINER: PVC 30 1/4" ROUND HOLE FOSS

HYD. COND.(CM/S)... = 0.291E-03

HEAD(CM)	FLOW(CC/S)
100.097	1.941
95.071	1.668
90.045	1.294
85.648	1.176
80.727	1.003

TAG: 44H/8 LINER: EPDM 30 1/4" ROUND HOLE FOSS

HYD. COND.(CM/S)... = 0.950E-04

HEAD(CM)	FLOW(CC/S)
101.607	1.339
94.906	1.295
88.206	1.140
80.989	1.023
72.433	0.952

TAG: 8F/19 LINER: HDPE 30 1/4" ROUND HOLE FOSS

HYD. COND.(CM/S)... = 0.108E-03

HEAD(CM)	FLOW(CC/S)
103.045	0.891
98.217	0.740
93.584	0.651
89.466	0.724
85.203	0.733

TAG: 8H/19 LINER: HDPE 30 1/4" ROUND HOLE HOECHST

HYD. COND.(CM/S)... = 0.108E-03

HEAD(CM)	FLOW(CC/S)
103.941	0.856
101.203	0.875
97.412	0.613

TAG: 7H/1 LINER: HDPE 30 1/4" ROUND HOLE HOECHST

HYD. COND.(CM/S)... = 0.360E-04

HEAD(CM)	FLOW(CC/S)
100.485	0.371
94.619	0.329
89.519	0.300
83.501	0.277
76.666	0.260

TAG: 26H/2 LINER: HDPE 30 6" SEAM SLIT HOECHST

HYD. COND.(CM/S)... = 0.402E-04

HEAD(CM)	FLOW(CC/S)
103.000	0.564
99.500	0.539
96.000	0.539
93.000	0.495
89.300	0.444

TAG: 185/8 LINER: HYPALON 36 1/32" ROUND HOLE

HYD. COND.(CM/S)... = 0.238E-04

HEAD(CM)	FLOW(CC/S)
39.378	0.018
39.312	0.061
39.210	0.063
39.126	0.042

TAG: 26F/21 LINER: HDPE 30 6" SEAM SLIT FOSS

HYD. COND.(CM/S)... = 0.129E-03

HEAD(CM)	FLOW(CC/S)
101.921	3.139
95.077	2.670
87.417	2.419
76.998	1.887
66.069	1.508
55.181	1.229

TAG: 21F/8 LINER: HDPE 30 6" VERT. SLIT FOSS

HYD. COND.(CM/S)... = 0.227E-04

HEAD(CM)	FLOW(CC/S)
104.756	0.323
102.178	0.273
100.322	0.251

TAG: 27H/19 LINER: HDPE 30 6" SEAM SLIT HOECHST

HYD. COND.(CM/S)... = 0.352E-04

HEAD(CM)	FLOW(CC/S)
103.143	0.496
96.323	0.436
89.197	0.391
82.581	0.339
75.965	0.317
69.501	0.267

TAG: 21H/8 LINER: HDPE 30 6" VERT. SLIT HOECHST

HYD. COND.(CM/S)... = 0.227E-04

HEAD(CM)	FLOW(CC/S)
104.248	0.348
98.733	0.298
93.115	0.241
88.007	0.221
83.227	0.204

TAG: 20H/8 LINER: HDPE 30 6" VERT. SLIT HOECHST

HYD. COND.(CM/S)... = 0.105E-03

HEAD(CM)	FLOW(CC/S)
100.187	0.924
94.622	0.792
90.026	0.678
85.941	0.615
81.999	0.556

TAG: 12H/15 LINER: HDPE 30 1/2" ROUND HOLE HOECHST

HYD. COND.(CM/S)... = 0.500E-04

HEAD(CM)	FLOW(CC/S)
102.786	0.002
102.736	0.004

TAG: 26F/7 LINER: HDPE 30 6" SEAM SLIT FOSS

HYD. COND.(CM/S)... = 0.500E-04

HEAD(CM)	FLOW(CC/S)
105.576	0.001
105.527	0.003
105.471	0.004
105.394	0.004

TAG: 25H/13 LINER: HDPE 30 6" SEAM SLIT HOECHST

HYD. COND.(CM/S)... = 0.500E-04

HEAD(CM)	FLOW(CC/S)
105.571	0.003
105.521	0.005
105.475	0.005

TAG: 184/19 LINER: HYPALON 36 1/32" ROUND HOLE

HYD. COND.(CM/S)... = 0.352E-04

HEAD(CM)	FLOW(CC/S)
39.777	0.039
39.719	0.024
39.626	0.049
39.514	0.674

TAG: 183/21 LINER: HYPALON 36 1/32" ROUND HOLE

HYD. COND.(CM/S)... = 0.129E-03

HEAD(CM)	FLOW(CC/S)
39.997	0.000
39.983	0.001
39.959	0.001
39.923	0.005

TAG: 9/2 LINER: HDPE 30 1/4" ROUND HOLE SLL

HYD. COND.(CM/S)... = 0.912E-04

HEAD(CM)	FLOW(CC/S)
74.042	0.239
71.647	0.275
68.774	0.280
66.618	0.214

TAG: 8/21 LINER: HDPE 30 1/4" ROUND HOLE SLL

HYD. COND.(CM/S)... = 0.912E-04

HEAD(CM)	FLOW(CC/S)
73.485	0.285
70.049	0.272
66.664	0.220

MEASUREMENTS OF FLOW RATES OF WATER THROUGH LINERS, OVER A
CLAY SUBBASE HAVING A CONDUCTIVITY OF 10^{-6} CM S $^{-1}$

TAG: 192/25 LINER: HDPE 30 1/32" ROUND HOLE

HYD. COND. (CM/S)... = 0.25000E-06

HEAD(CM)	FLOW(CC/S)
101.750	0.03725

Q-CALCULATED FROM THE FINAL READING = 0.03725

TAG: 6/15 LINER: HDPE 30 1/4" ROUND HOLE

HYD. COND. (CM/S)... = 0.36600E-06

HEAD(CM)	FLOW(CC/S)
45.095	0.00193

Q-CALCULATED FROM THE FINAL READING = 0.00193

TAG: 6/15 LINER: HDPE 30 1/4" ROUND HOLE

HYD. COND. (CM/S)... = 0.36600E-06

HEAD(CM)	FLOW(CC/S)
75.488	0.00036
75.376	0.00194

Q-CALCULATED FROM THE FINAL READING = 0.00133

TAG: 4/15 LINER: HDPE 30 1/4" ROUND HOLE

HYD. COND. (CM/S)... = 0.36600E-06

HEAD(CM)	FLOW(CC/S)
75.463	0.00246
75.283	0.00249

Q-CALCULATED FROM THE FINAL READING = 0.00248

TAG: 10/11 LINER: HDPE 30 1/2" ROUND HOLE

HYD. COND. (CM/S)... = 0.15000E-06

HEAD(CM)	FLOW(CC/S)
45.458	0.00106
45.386	0.00066

Q-CALCULATED FROM THE FINAL READING = 0.00085

2

TAG:12/7 LINER:HDPE 30 1/2" ROUND HOLE

HYD. COND. (CM/S)... = 0.22900E-06

HEAD(CM) FLOW(CC/S)

74.293 0.00174

74.124 0.00369

Q-CALCULATED FROM THE FINAL READING = 0.00217

TAG:11/12 LINER: HDPE 30 1/2" ROUND HOLE

HYD. COND. (CM/S)... = 0.22900E-06

HEAD(CM) FLOW(CC/S)

44.391 0.00011

Q-CALCULATED FROM THE FINAL READING = 0.00011

TAG: 12/7 LINER: HDPE 30 1/2" ROUND HOLE

HYD. COND. (CM/S)... = 0.22900E-06

HEAD(CM) FLOW(CC/S)

46.242 0.00203

46.172 0.00058

46.151 0.00015

Q-CALCULATED FROM THE FINAL READING = 0.00074

TAG: 11/12 LINER: HDPE 30 1/2" ROUND HOLE

HYD. COND. (CM/S)... = 0.22900E-06

HEAD(CM) FLOW(CC/S)

74.265 0.00135

74.213 0.00074

Q-CALCULATED FROM THE FINAL READING = 0.00110

TAG: 10/11 LINER: HDPE 30 1/2" ROUND HOLE

HYD. COND. (CM/S)... = 0.15000E-06

HEAD(CM) FLOW(CC/S)

75.030 0.00210

Q-CALCULATED FROM THE FINAL READING = 0.00210

TAG: 13H/7 LINER: HDPE 30 1/16" ROUND HOLE HOECHST

HYD. COND. (CM/S)... = 0.65100E-06

HEAD(CM)	FLOW(CC/S)
105.450	0.00330
105.400	0.00000
105.300	0.00391

Q-CALCULATED FROM THE FINAL READING = 0.00154

TAG: 14H/9 LINER: HDPE 30 1/16" ROUND HOLE HOECHST

HYD. COND. (CM/S)... = 0.82900E-06

HEAD(CM)	FLOW(CC/S)
103.050	0.00724
102.650	0.00000
102.100	0.00771

Q-CALCULATED FROM THE FINAL READING = 0.00771

TAG: 15H/11 LINER: HDPE 30 1/16" ROUND HOLE HOECHST

HYD. COND. (CM/S)... = 0.45200E-06

HEAD(CM)	FLOW(CC/S)
102.350	0.00161
102.250	0.00252
102.100	0.00392
101.950	0.00235

Q-CALCULATED FROM THE FINAL READING = 0.00256

TAG: 13F/7 LINER: HDPE 30 1/16" ROUND HOLE FOSS

HYD. COND. (CM/S)... = 0.65100E-06

HEAD(CM)	FLOW(CC/S)
105.850	0.00317
105.750	0.00302
105.700	0.00000
105.600	0.00192
105.500	0.00000

Q-CALCULATED FROM THE FINAL READING = 0.00172

TAG: 14F/9 LINER: HDPE 30 1/16" ROUND HOLE FOSS

HYD. COND. (CM/S)... = 0.02900E-06

HEAD(CM)	FLOW(CC/S)
107.200	0.00788
106.900	0.01188
106.350	0.01861

Q-CALCULATED FROM THE FINAL READING = 0.01345

TAG: 15F/11 LINER: HDPE 30 1/16" ROUND HOLE FOSS

HYD. COND. (CM/S)... = 0.20700E-06

HEAD(CM)	FLOW(CC/S)
102.650	0.00435
102.500	0.00192
102.400	0.00000
102.350	0.00297
102.300	0.00000

Q-CALCULATED FROM THE FINAL READING = 0.00170

TAG: 4H/12 LINER: HDPE 30 1/4" ROUND HOLE HOECHST

HYD. COND. (CM/S)... = 0.36900E-06

HEAD(CM)	FLOW(CC/S)
103.400	0.00289
103.250	0.00290

Q-CALCULATED FROM THE FINAL READING = 0.00290

TAG: 5H/13 LINER: HDPE 30 1/4" ROUND HOLE HOECHST

HYD. COND. (CM/S)... = 0.50600E-06

HEAD(CM)	FLOW(CC/S)
103.350	0.00435
103.100	0.00891
102.900	0.00290
102.800	0.00000
102.650	0.00289

Q-CALCULATED FROM THE FINAL READING = 0.00335

TAG: 4F/12 LINER: HDPE 30 1/4" ROUND HOLE FOSS

HYD. COND. (CM/S)... = 0.22900E-06

HEAD(CM)	FLOW(CC/S)
103.750	0.00601
102.200	0.00349
102.050	0.00270
102.000	0.00000
101.900	0.00205

Q-CALCULATED FROM THE FINAL READING = 0.00501

TAG: 5F/13 LINER: HDPE 30 1/4" ROUND HOLE FOSS

HYD. COND. (CM/S)... = 0.58300E-06

HEAD(CM)	FLOW(CC/S)
104.500	0.00811
104.300	0.00591
104.100	0.00534

Q-CALCULATED FROM THE FINAL READING = 0.00625

TAG: 6F/15 LINER: HDPE 30 1/4" ROUND HOLE FOSS

HYD. COND. (CM/S)... = 0.36600E-06

HEAD(CM)	FLOW(CC/S)
103.650	0.00268
102.950	0.00174
102.850	0.00273
102.200	0.01178

Q-CALCULATED FROM THE FINAL READING = 0.00397

TAG: 6H/15 LINER: HDPE 30 1/4" ROUND HOLE HOECHST

HYD. COND. (CM/S)... = 0.36600E-06

HEAD(CM)	FLOW(CC/S)
101.650	0.01001
101.350	0.01086
101.150	0.00145
101.050	0.00096

Q-CALCULATED FROM THE FINAL READING = 0.00347

TAG: 10H/25 LINER: HDPE 30 1/2" ROUND HOLE HOECHST

HYD. COND. (CM/S)... = 0.25000E-06

HEAD(CM)	FLOW(CC/S)
105.350	0.00533
105.250	0.00295
105.150	0.01444
104.850	0.00515
104.550	0.00274
104.400	0.00592
104.250	0.00267

Q-CALCULATED FROM THE FINAL READING = 0.00454

TAG: 11H/7 LINER: HDPE 30 1/2" ROUND HOLE HOECHST

HYD. COND. (CM/S)... = 0.65100E-06

HEAD(CM)	FLOW(CC/S)
105.400	0.00001
105.250	0.00266

Q-CALCULATED FROM THE FINAL READING = 0.00400

TAG: 12F/15 LINER: HDPE 30 1/2" ROUND HOLE FOSS

HYD. COND. (CM/S)... = 0.36600E-06

HEAD(CM)	FLOW(CC/S)
101.400	0.00493

Q-CALCULATED FROM THE FINAL READING = 0.00493

TAG: 11F/25 LINER: HDPE 30 1/2" ROUND HOLE FOSS

HYD. COND. (CM/S)... = 0.25000E-06

HEAD(CM)	FLOW(CC/S)
103.700	0.00580
103.150	0.00343

Q-CALCULATED FROM THE FINAL READING = 0.00441

TAG:10F/25 LINER: HDPE 30 1/2" ROUND HOLE FOSS

HYD. COND. (CM/S)... = 0.25000E-06

HEAD(CM)	FLOW(CC/S)
104.400	0.00564

Q-CALCULATED FROM THE FINAL READING = 0.00564

TAG: 21H/12 LINER: HDPE 30 6" VERT. SLIT HOECHST

HYD. COND. (CM/S)... = 0.22900E-06

HEAD(CM)	FLOW(CC/S)
103.724	0.00663
103.598	0.00293

Q-CALCULATED FROM THE FINAL READING = 0.00439

TAG:19F/12 LINER: HDPE 30 6" VERT SLIT FOSS

HYD. COND. (CM/S)... = 0.22900E-06

HEAD(CM)	FLOW(CC/S)
102.500	0.00200
102.050	0.00125
101.550	0.00096

Q-CALCULATED FROM THE FINAL READING = 0.00136

TAG:20F/13 LINER: HDPE 30 6" VERT. SLIT FOSS

HYD. COND. (CM/S)... = 0.50600E-06

HEAD(CM)	FLOW(CC/S)
104.300	0.00431
103.950	0.00144
103.600	0.00439
103.150	0.00291
102.550	0.00655
102.050	0.00231
101.850	0.00469

Q-CALCULATED FROM THE FINAL READING = 0.00419

TAG: 21F/11 LINER: HDPE 30 6" VERT. SLIT FOSS

HYD. COND. (CM/S)... = 0.28700E-06

HEAD(CM)	FLOW(CC/S)
104.888	0.00087
104.858	0.00109

Q-CALCULATED FROM THE FINAL READING = 0.00100

TAG: 27H/11 LINER: HDPE 30 6" SEAM SLIT HOECHST

HYD. COND. (CM/S)... = 0.15000E-06

HEAD(CM)	FLOW(CC/S)
104.153	0.00279

Q-CALCULATED FROM THE FINAL READING = 0.00279

TAG: 25F/13 LINER: HDPE 30 6" SEAM SLIT FOSS

HYD. COND. (CM/S)... = 0.50700E-06

HEAD(CM)	FLOW(CC/S)
105.246	0.00164

Q-CALCULATED FROM THE FINAL READING = 0.00164

TAG: 26H/7 LINER: HDPE 30 6" SEAM SLIT HOECHST

HYD. COND. (CM/S)... = 0.65100E-06

HEAD(CM)	FLOW(CC/S)
106.142	0.00347
106.020	0.00362

Q-CALCULATED FROM THE FINAL READING = 0.00355

TAG: 27F/25 LINER: HDPE 30 6" SEAM SLIT FOSS

HYD. COND. (CM/S)... = $0.25000E-06$

HEAD(CM)	FLOW(CC/S)
104.344	0.09776

Q-CALCULATED FROM THE FINAL READING = 0.09776

TAG: 38F/12 LINER: HYPALON 1/4" ROUND HOLE FOSS

HYD. COND. (CM/S)... = $0.22900E-06$

HEAD(CM)	FLOW(CC/S)
101.950	0.00209

Q-CALCULATED FROM THE FINAL READING = 0.00209

TAG: 36F/7 LINER: HYPALON 1/4" ROUND HOLE FOSS

HYD. COND. (CM/S)... = $0.65100E-06$

HEAD(CM)	FLOW(CC/S)
103.300	0.00167

Q-CALCULATED FROM THE FINAL READING = 0.00167

DERIVATION OF CALCULATIONAL PROCEDURE USED TO
REDUCE THE PERMEAMETER DATA

Permeameter Data Reduction

Flow conditions assumed in the calculation are shown in Figure A1. The leachate passed through the flaw at the center of the liner and spread laterally between the liner and the soil with simultaneous infiltration into the soil.

Figure A2 shows an element of liquid and the forces acting on it once the steady flow conditions are achieved.

Considering the equilibrium of the fluid element,

$$[(p+dp)(r+dr)d\theta - pr d\theta]2y + [1/2(r+dr)^2 d\theta - 1/2 r^2 d\theta]2\tau - 2(p+dp/2) dr \cdot 2y \cdot \sin(d\theta/2) = 0 \quad (1)$$

where:

p = liquid pressure at radial distance r ,
 r = radial distance,
 y = distance from the middle plane,
 θ = radial coordinate, and
 τ = viscous shear on any plane at distance y from the middle plane.

From Eq (1) it follows that:

$$[p \cdot dr \cdot d\theta + dp \cdot r \cdot d\theta]2y + (r \cdot dr \cdot d\theta)2\tau - (p \cdot d\theta \cdot dr)2y = 0, \quad (2)$$

$$dp \cdot r \cdot d\theta \cdot 2y + 2r \cdot dr \cdot d\theta \cdot \tau = 0 \text{ and} \quad (3)$$

$$\tau = -y \cdot \frac{dp}{dr} \quad (4)$$

$$\text{For a Newtonian fluid, } \tau = -\eta \frac{du}{dy} \quad (5)$$

where η is the absolute viscosity of the liquid and u is the lateral flow velocity at distance y from the middle plane.

$$\text{From (4) and (5) it follows that } -y \frac{dp}{dr} = -\eta \frac{du}{dy} \quad (6)$$

$$\text{Integrating (6) yields: } u = \frac{1}{2\eta} \left(-\frac{dp}{dr} \right) \left(\frac{t^2}{4} - y^2 \right) \quad (7)$$

where t is the clearance between the liner and the subbase.

The flow rate, Q , can be obtained by integrating over the thickness as follows:

$$Q = 2 \int_0^{t/2} u dy \cdot 2\pi r = 4\pi r \cdot \int_0^{t/2} u dy, \quad (8)$$

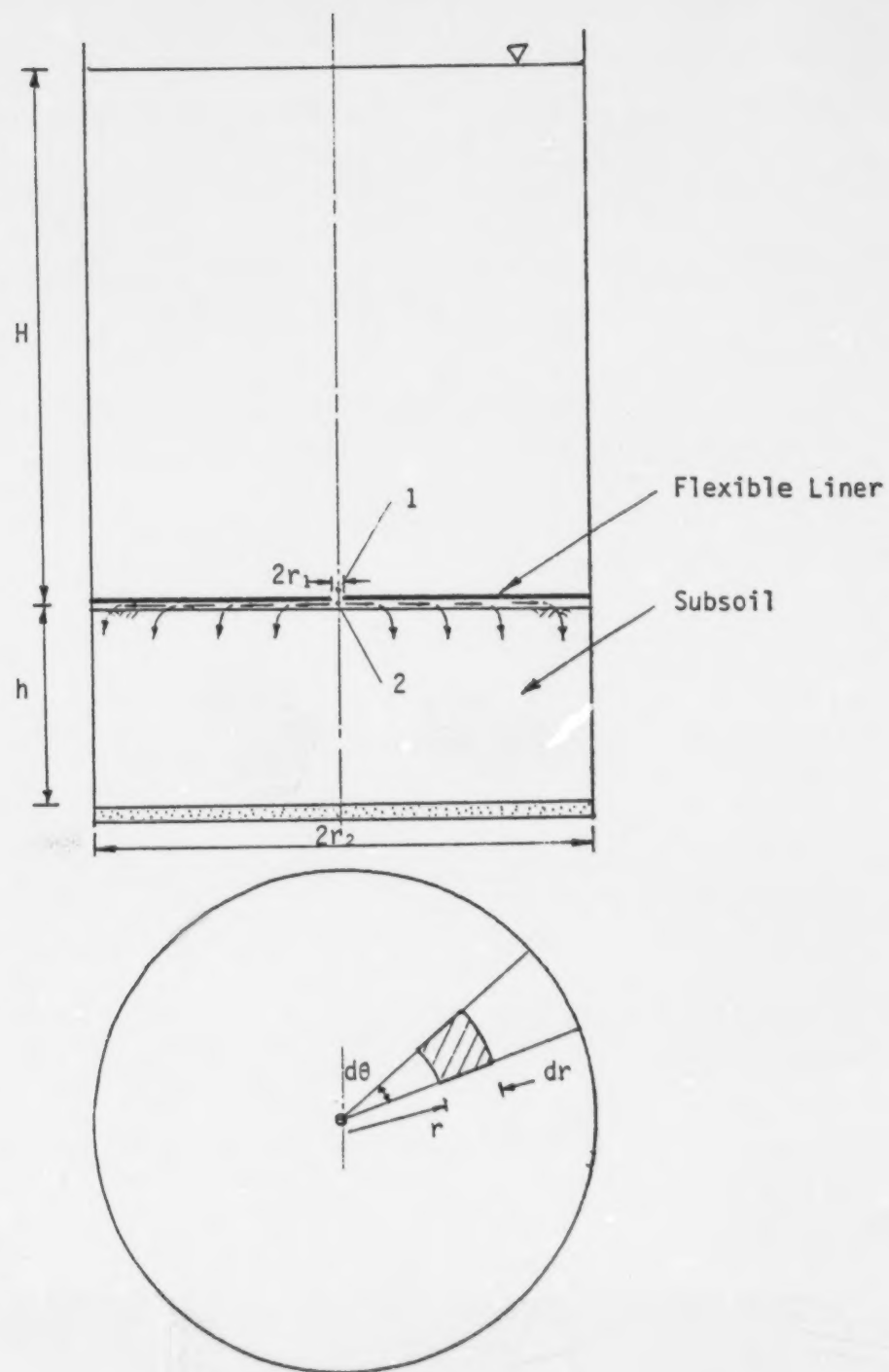


Figure A1. Flow conditions assumed in the calculations.

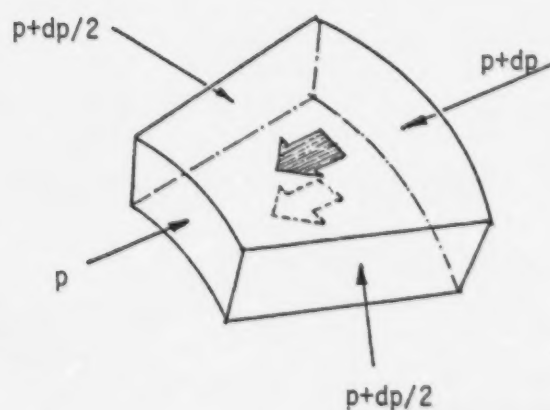
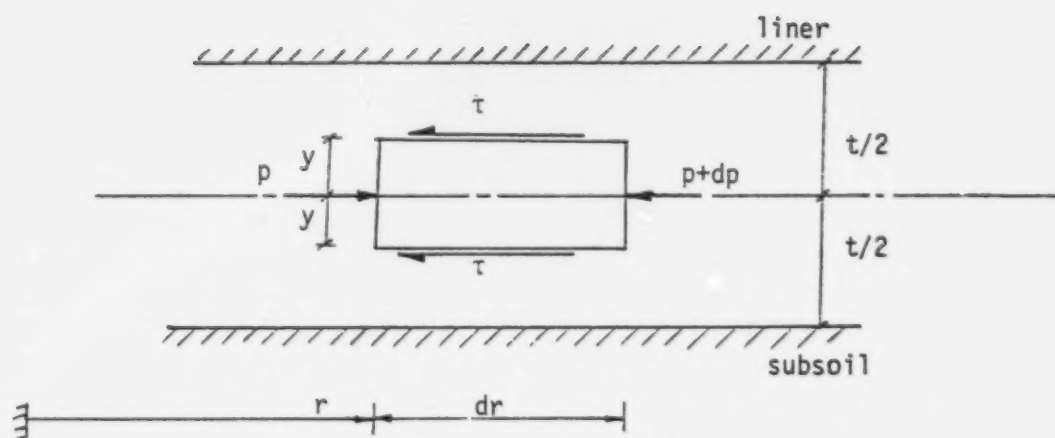


Figure A.. Forces acting on an element of fluid.

$$Q = \frac{-2\pi r}{\eta} \left[\frac{dp}{dr} \right] \left[\frac{t^2}{4} y - \frac{y^3}{3} \right]_0^{t/2}, \quad (9)$$

$$Q = \frac{-2\pi r}{\eta} \left(\frac{dp}{dr} \right) \frac{t^3}{12}, \text{ and} \quad (10)$$

$$Q = - \frac{\pi r t^3}{6\eta} \left(\frac{dp}{dr} \right). \quad (11)$$

Due to the confining effect of the permeameter wall, considerable pressure head can develop between the liner and the soil, which would tend to accelerate the infiltration rate of liquid into the soil.

The rate of infiltration, (I) can thus be estimated as:

$$I = K \left(\frac{p/\rho g + h}{h} \right) \quad (12)$$

where:

I = infiltration rate of liquid into soil,
 K = hydraulic conductivity of the soil for the given liquid,
 ρ = density of the given liquid,
 g = acceleration of gravity, and
 h = height of soil layer.

Considering the volume infiltrating into an incremental annular area of radius, r and width dr yields:

$$dq = 2 \pi r dr K \left(\frac{p + h \rho g}{h \rho g} \right). \quad (13)$$

Integrating, Eq (13) yields:

$$q = \int_0^r 2\pi r dr K \left(\frac{p + h \rho g}{h \rho g} \right), \quad (14)$$

$$q = \frac{2\pi K}{h\rho g} \int_0^r pr \, dr + 2\pi K \int_0^r r \, dr, \text{ or } (15)$$

$$q = \frac{2\pi K}{h\rho g} \int_0^r pr \, dr + \pi r^2 K. \quad (16)$$

Since, $\left[\begin{array}{l} \text{Lateral flow, } Q, \\ \text{at radius } r \end{array} \right] = \left[\begin{array}{l} \text{Flow entering through} \\ \text{the flaw, } Q_1 \end{array} \right] - \left[\begin{array}{l} \text{Volume infiltrated over} \\ \text{a circular area, } - r^2 \end{array} \right]$

It follows that:

$$Q = Q_1 - \frac{2\pi K}{h\rho g} \int_0^r pr \, dr - \pi r^2 K. \quad (17)$$

Differentiating Eq (17) yields:

$$\frac{dQ}{dr} = \frac{-2\pi K}{h\rho g} pr - 2\pi r K \quad (18)$$

Combining Eqs (18) and (11) yields:

$$\frac{-\pi t^3}{6\eta} \frac{d}{dr} \left(r \frac{dp}{dr} \right) = \frac{-2\pi K}{h\rho g} pr - 2\pi r K. \quad (19)$$

Therefore, the governing differential equation would be,

$$\frac{d}{dr} \left(r \frac{dp}{dr} \right) - \frac{12\eta K}{h\rho g t^3} (pr) = \frac{12\eta K}{t^3} r. \quad (20)$$

The particular solution to this differential equation is given by,

$$p = -h\rho g. \quad (21)$$

To find the complementary solution, the transformation $u = \lambda r$ was used. The homogenous form of Eq (20) then reduces to the following:

$$\frac{d^2 p}{du^2} + \frac{1}{u} \frac{dp}{du} - p = 0. \quad (22)$$

The solution to this equation would be;

$$p = A I_0(u) + B K_0(u). \quad (23)$$

Thus, the general solution to the governing differential equation can be expressed as:

$$p = A I_0(\lambda r) + B K_0(\lambda r) - h\rho g, \quad (24)$$

where $I_n(Z)$ = Modified Bessel Function of the first kind and nth order,

$K_n(Z)$ = Modified Bessel Function of the second kind and nth order, and

A, B = Constants to be determined by the boundary conditions.

The definitions of the Modified Bessel Functions are as follows:

$$I_n(Z) = \sum_{r=0}^{\infty} \frac{(z/2)^{n+2r}}{r! \Gamma(n+r+1)}, \quad (25)$$

where Γ = the gamma function, and

$$K_n(Z) = \frac{\pi \{ I_{-n}(Z) - I_n(Z) \}}{2 \sin n\pi} \quad (26)$$

The boundary conditions corresponding to the flow situation existing in the permeameter are as follows:

$$p = p_3 \text{ at } r = r_1 \quad (27)$$

$$\text{and } Q = 0 \text{ at } r = r_2. \quad (28)$$

The solution obtained for the above boundary conditions are given in Equations (29) and (30) below:

$$p = A I_0 (\lambda r) + B K_0 (\lambda r) - h \rho g, \quad (29)$$

$$Q = - \frac{\pi r t^3}{6\eta} \lambda (A I_1 (\lambda r) - B K_1 (\lambda r)), \quad (30)$$

where:

$$A = \frac{H_3 \rho g}{I_0 (\lambda r_1) + \frac{I_1 (\lambda r_2)}{K_1 (\lambda r_2)} \cdot K_0 (\lambda r_1)}, \quad (31)$$

$$B = \frac{H_3 \rho g}{K_0 (\lambda r_1) + \frac{K_1 (\lambda r_2)}{I_1 (\lambda r_2)} \cdot I_0 (\lambda r_1)}, \quad (32)$$

$$\text{and } H_3 = \left(\frac{P_3}{\rho g} + h \right). \quad (33)$$

Equations (29) and (30) now allow one to estimate the liquid pressure and flow rate at any given radial distance within the permeameter.

Partitioning of Head Loss

It can be seen that H_3 in the equations (31) through (33) represents the total head available for flow in the lateral direction and seepage through the soil after head losses have taken place at the liner flaw. The magnitude of these losses largely depends on the flaw size and the flow rate through the orifice. When leakage occurs through a large size orifice into a subbase of low permeability soil, the head loss component at the flaw will be negligibly small when compared with that which occurs through the soil. Under these circumstances, the leakage rate will be controlled by the soil rather than the orifice. However, the situation is quite the reverse when leakage occurs through a small size orifice into a relatively permeable subbase. In this case, the head loss that occurs at the liner flaw will predominate and will be the controlling factor in determining the flow rate. This section describes how the head losses at the flaw are estimated.

The head loss that occurs at the orifice is determined as the sum of two components as follows:

$$\left\{ \begin{array}{l} \text{Head Loss at} \\ \text{the liner} \\ \text{flaw} \end{array} \right\} = \left\{ \begin{array}{l} \text{Head loss due to} \\ \text{convergence at} \\ \text{the orifice, } H_1 \end{array} \right\} + \left\{ \begin{array}{l} \text{Head loss due to viscous} \\ \text{resistance to flow through} \\ \text{the thickness of the liner,} \\ H_2 \end{array} \right\}$$

Referring to Figure A1 and using Bernoulli's principle,

$$\left[\frac{p_1}{\rho g} + \frac{v_1^2}{2g} + Z \right] = \left[\frac{p_2}{\rho g} + \frac{v_2^2}{2g} + Z \right] + H_1, \quad (34)$$

where v_1 = liquid velocity just before entering the orifice,
Point 1 in Figure A1.

v_2 = liquid velocity immediately after passing through
the orifice, Point 2 in Figure A1.

Since $v_1 \approx 0$ and $v_2 = v$ the Equation simplifies to,

$$H_1 = \left(\frac{p_1 - p_2}{\rho g} \right) - \frac{v^2}{2g}. \quad (35)$$

When the head loss is expressed in terms of the coefficient of velocity, C,

$$v = C \left[2g (p_1 - p_2) / \rho g \right]^{1/2}. \quad (36)$$

Thus,

$$\frac{1}{C^2} \frac{v^2}{2g} = \frac{p_1 - p_2}{\rho g}. \quad (37)$$

By substituting into Eq (35),

$$H_1 = \frac{v^2}{2g} \left(\frac{1}{C^2} - 1 \right). \quad (38)$$

In the present analysis, the coefficient C was determined as 0.65 using Figure A3.

$$\text{Therefore, } H_1 = 1.367 \frac{V^2}{2g} \quad (39)$$

It should be noted that in the above analysis, the head loss that occurs as the leachate flows through the FML has been disregarded. Therefore, this component of the head loss has to be taken into account separately.

Using Darcy's law,

$$H_2 = f \frac{T}{d} \cdot \frac{V^2}{2g}, \quad (40)$$

where f = friction factor

T = thickness of the FML

and V = flow velocity through the flaw in the FML.

The flow rates observed in the permeameter tests indicated that they had Reynolds Numbers (Re) which corresponded to laminar flow. Therefore, from the Moody diagram (Figure A4),

$$f = \frac{64}{R_e} = \frac{64}{Vd/\nu}, \quad (41)$$

where ν = kinematic viscosity of the liquid.

$$\text{Thus, } H_2 = \left(\frac{64\nu}{Vd} \cdot \frac{T}{d} \right) \frac{V^2}{2g}. \quad (42)$$

The results shown in Eqs (30) through (33) can be combined to give H_3 in terms of the leakage rate, Q_1 . Similarly, Eqs (39) and (42) can be simplified to obtain expressions for H_2 and H_3 in terms of Q_1 . These results can be summarized as follows:

$$H_1 = 0.06925 \frac{Q_1^2}{gr_1^4}, \quad (43)$$

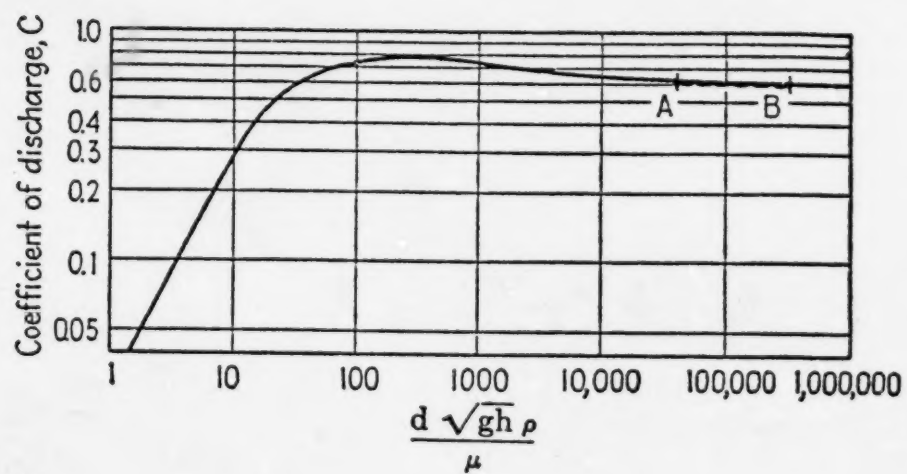


Figure A3. The coefficient of discharge used in estimating the head losses at the orifice. (Brater and King 1976)

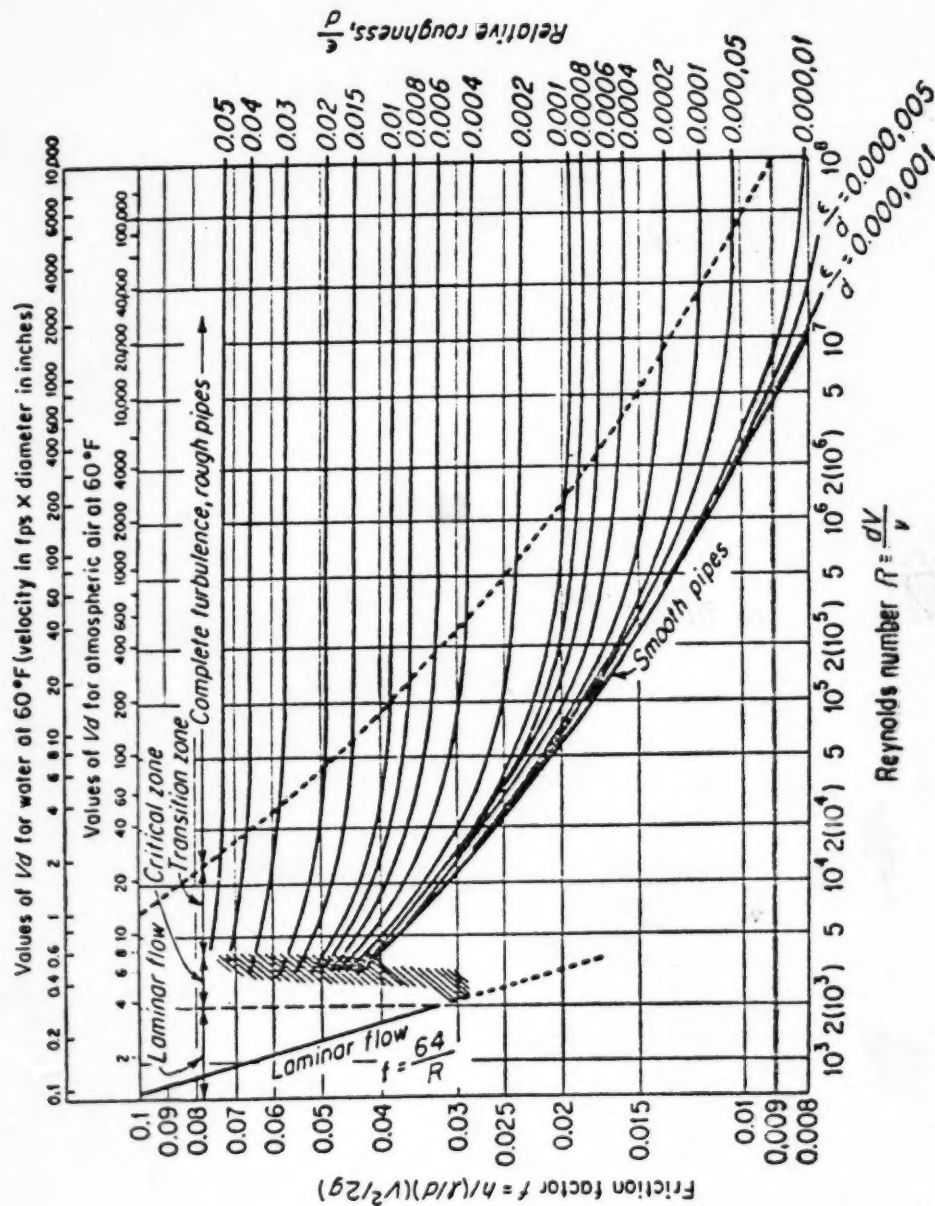


Figure A4. The Moody diagram. (Moody, 1944).

$$H_2 = 2.5465 \frac{\eta T Q_1}{g r_1^4}, \text{ and} \quad (44)$$

$$H_3 = \frac{Q_1 / \pi r_1 t^3 \rho g}{6\eta} \cdot \frac{K_1(\lambda r_1)}{K_0(\lambda r_1) + \frac{K_1(\lambda r_1)}{I_1(\lambda r_2)} \cdot I_0(\lambda r_1)} - \frac{I_1(\lambda r_1)}{I_0(\lambda r_1) + \frac{I_1(\lambda r_2)}{K_1(\lambda r_2)} \cdot K_0(\lambda r_1)}, \quad (45)$$

$$\text{where } \lambda = \sqrt{\frac{12 \eta K}{h \rho g t^3}}$$

By substituting typical numerical values in Eqs (43) through (45), it can be seen that in all the cases either H_1 or H_3 is the controlling head loss component. The head loss that occurs during flow through the hole in the liner, H_2 , was negligibly small in comparison with H_1 and H_3 .

Effect of Radial Distance from Flow on Pressure and Flow Rate in Permeameters

The liquid pressure and flow rate in the lateral direction was transformed into the following non-dimensional form:

$$\text{Pressure, } p = A I_0(\lambda r) + B K_0(\lambda r) - h \rho g$$

Therefore,

$$\hat{p} = \frac{p}{p_3} = \hat{A} I_0(\lambda r) + \hat{B} K_0(\lambda r) - \frac{h \rho g}{p_3} \quad (46)$$

$$\text{where } \hat{A} = \frac{A}{p_3},$$

$$\text{and } \hat{B} = \frac{B}{p_3}.$$

$$\text{The flow rate, } Q = \frac{\pi t^3}{6\eta} (\lambda r) [B K_1(\lambda r) - A I_1(\lambda r)] \text{ and} \quad (47)$$

$$\hat{Q} = \frac{Q}{\pi t^3 p_3 / 6\eta} = (\lambda r) (\hat{B} K_1(\lambda r) - \hat{A} I_1(\lambda r)). \quad (48)$$

To examine whether the solutions obtained for $\hat{p}$ and $\hat{Q}$ follow proper trends, the results of Equations (46 and 48) are plotted in Figure A5. The non-dimensional flow rate, ($\hat{Q}$) decreased from a maximum of 0.13 directly below the flaw to zero flow at 0.6 which corresponds to the permeameter wall. As would be expected, the non-dimensional pressure ($\hat{p}$) at distance zero directly below the flaw was one and decreased sharply as the distance increased to 0.2, after which it decreased only very slightly. These relations, however, are not general since the constants A and B can only be

determined for specific boundary conditions. The following parameters were used in estimating the boundary conditions λr_1 and λr_2 in the results shown in Figure A5.

$$\begin{aligned} r_1 &= 0.3174 \text{ cm} & \eta &= 8.95 \text{ E-03 poise}_1 \\ r_2 &= 28.6 \text{ cm} & K &= 3.40 \text{ E-04 cm s}^{-1} \\ t^2 &= 0.015 \text{ cm} & \rho &= 1.00 \text{ g cm}^{-3} \\ h &= 25.0 \text{ cm} \end{aligned}$$

The results tabulated in Table A1 show that the flow rate becomes zero at the outer boundary due to the confining effect of the permeameter wall. It is also apparent that the pressure gradient, which causes lateral flow, asymptotically reaches zero at the outer boundary.

TABLE A1. CALCULATED NON-DIMENSIONAL PRESSURE ($\hat{p}$)
COMPUTED AS THE PRESSURE AT RADIAL DISTANCE r
DIVIDED BY THE PRESSURE DIRECTLY BELOW THE FLAW
AND CALCULATED NON-DIMENSIONAL FLOW RATE ($\hat{Q}$)
COMPUTED AS THE FLOW AT RADIAL DISTANCE r DIVIDED
BY THE FLOW THROUGH THE SUBBASE WITHOUT ANY FML AT
VARIOUS NON-DIMENSIONAL RADIAL DISTANCES (λr) FROM
THE CENTER.

λr	$\hat{p}$	$\hat{Q}$
0.00667	1.00000	0.13428
0.06607	0.69313	0.13212
0.12548	0.60970	0.12707
0.18488	0.56175	0.11945
0.24429	0.52975	0.10939
0.30369	0.50719	0.09699
0.36309	0.49111	0.08227
0.42250	0.47987	0.06524
0.48190	0.47251	0.04589
0.54131	0.46839	0.02416
0.60071	0.46709	0.0

Extrapolation to Field Conditions

The calculational procedure discussed thus far was developed to simulate the conditions that exist in the laboratory permeameter. It was necessary to modify the equations to predict the potential leakage rates under field conditions. The confining effect introduced by permeameter walls was removed by replacing the boundary conditions with those representative of the conditions that would exist in the field. Furthermore, the infiltration rate was assumed to be uniform and equal to the saturated conductivity of the subbase.

Under the assumption of uniform infiltration rate $= K_{\text{sat}}$, Eq (13) was modified as follows:

$$dp = 2\pi r dr. K. \quad (49)$$

Integrating Eq (46) yields:

$$q = \pi r^2 K. \quad (50)$$

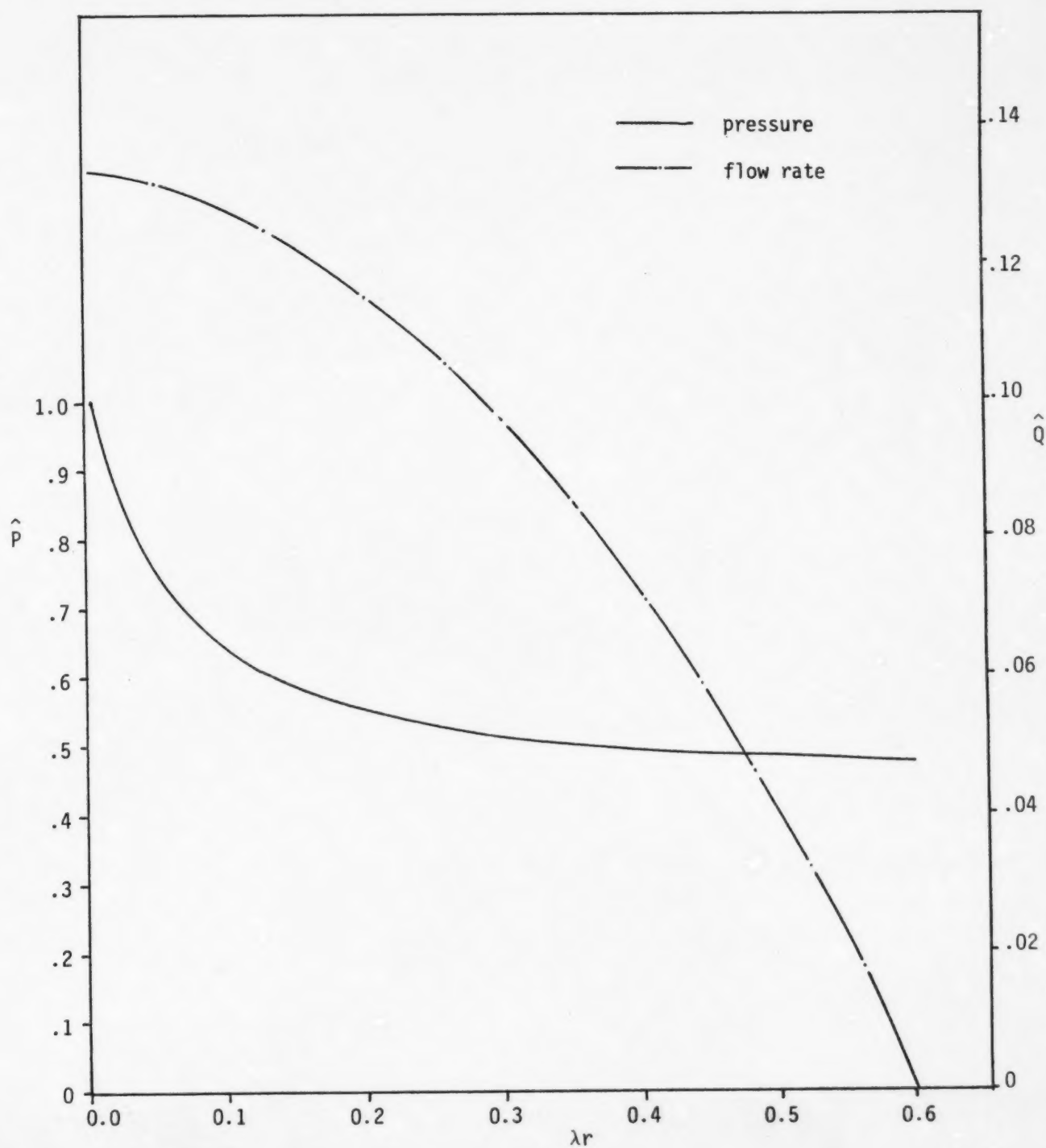


Figure A5. Non-dimensional pressure ($\hat{p}$) and flow rate ($\hat{Q}$) as a function of non-dimensional radial distance (λr) from the flaw.

$$\text{Therefore, } Q = Q_1 - \pi r^2 K. \quad (51)$$

Combining this result with Eq (11),

$$-\frac{\pi r t^3}{6\eta} \left(\frac{dp}{dr}\right) = Q_1 - \pi r^2 K, \text{ and} \quad (52)$$

$$\frac{dp}{dr} = \frac{6\eta K}{t^3} r - \frac{6\eta Q_1}{\pi t^3} \cdot \frac{1}{r}. \quad (53)$$

Solving for p yields:

$$p = \frac{6\eta K}{t^3} \cdot \frac{r^2}{2} - \frac{6\eta Q_1}{\pi t^3} \ln(r) + \text{constant}. \quad (54)$$

Using the boundary conditions,

$$\text{at } r = r_1 \quad p = p_3, \text{ and}$$

$$\text{at } r = r_2 \quad p = 0, \text{ then}$$

$$p_3 = \frac{6\eta K}{t^3} \cdot \frac{r_1^2}{2} - \frac{6\eta Q_1}{\pi t^3} \ln(r) + \text{constant}, \quad (55)$$

$$0 = \frac{6\eta K}{t^3} \cdot \frac{r^2}{2} - \frac{6\eta Q_1}{\pi t^3} \ln(r_2) + \text{constant}. \quad (56)$$

Taking the difference yields:

$$p_3 = \frac{6\eta Q_1}{\pi t^3} \ln\left(\frac{r_2}{r_1}\right) - \frac{3\eta K}{t^3} (r_2^2 - r_1^2). \quad (57)$$

Since the rate of infiltration is uniform,

$$Q_1 = \pi r_2^2 K, \quad (58)$$

$$p_3 = \frac{6\eta K}{t^3} r_2^2 \ln \left(\frac{r_2}{r_1} \right) - \frac{3\eta K}{t^3} (r_2^2 - r_1^2), \quad (59)$$

and

$$p_3 = \frac{3\eta K r_1^2}{t^3} \left[2 \left(\frac{r_2}{r_1} \right)^2 \ln \left(\frac{r_2}{r_1} \right) - \left(\frac{r_2}{r_1} \right)^2 + 1 \right] \quad (60)$$

Therefore, the head loss component associated with infiltration and lateral flow is given by,

$$H_3 = \frac{3\eta K}{\rho g t^3} r_1^2 \left((\hat{r})^2 \{ 2 \ln (\hat{r}) - 1 \} + 1 \right), \quad (61)$$

where $\hat{r} = r_2/r_1$.

The other head loss terms, given by (43) and (44), can be expressed in term of r_2 in the following manner:

$$H_1 = 0.6835 \frac{K^2}{g} \left(\frac{r_2}{r_1} \right)^4 = 0.6835 \frac{K^2}{g} (\hat{r})^4 \quad (62)$$

and

$$H_2 = \frac{8\eta K T}{\rho g r_1^2} \left(\frac{r_2}{r_1} \right)^2 = \frac{8\eta K T}{\rho g r_1^2} (\hat{r})^2. \quad (63)$$

The results given in Equations (58), (59), (60), and (61) can be used via the computer program listed in Appendix B to predict the leakage rate that would be expected to occur under specified conditions without the presence of the confining walls. In addition, the equations are also capable of predicting the radius of wetted area.

APPENDIX B

CALCULATIONAL PROCEDURE USED TO PREDICT LEAKAGE RATE
UNDER FIELD CONDITIONS

USERS GUIDE

The program "LEAKRATE" is based upon the calculational procedure developed to predict the leakage rate through a circular hole in a flexible liner.

The program requires the following as input data:

	<u>Variable Name</u>	<u>Description</u>
Card 1	CONDK	Conductivity of the subsoil (cm s^{-1}).
	TH	Liner Thickness (cm)
	R1	Radius of the liner flaw (cm)
	N	Number of heads at which leak rate is to be determined.
Card 2:	H(I), I = 1,N	Head of water above the liner level (cm).

Cards 1 and 2 may be repeated for any number of datasets. Card 1*END denotes the end of data file.

The computer must have access to an IMSL Library.

Notes:

1. If the units given above are used, the calculated flow rates will be in $\text{cm}^3 \text{s}^{-1}$. However, any other consistent system of units may be used.
2. The program uses unformatted input. Therefore, the input data need not conform to a specific format. The data values must be separated by one or more blank spaces. Each card accomodates a maximum of 80 characters. Data values in excess of this can be continued on the next line (see sample datafile).
3. The input data should be kept within the following ranges.
Soil conductivity: 1×10^{-7} - $1 \times 10^{-3} \text{ cm s}^{-1}$
Water head: 10 - 1000 cm
Hole radius: 0.04 - 0.635 cm
(1/64" - 1/4")
Liner thickness: 0.051 - 0.254 cm
(20 - 100 mils)

4. The following constants are built into the program as leachate properties.
Density, $\text{RHO} = 1.0 \text{ g cm}^3$
Absolute viscosity, $\text{ETA} = 8.95 \times 10^{-3}$ poises
These constants are typical values for water. Appropriate changes need to be made when some other leachate is being investigated.
5. The output of the program gives the following information.
- a) Expected Flow Rate in $\text{cm}^3 \text{ s}^{-1}$ for Model I,
i.e., for the laboratory permeameter set up.
 - b) Expected Flow Rate in $\text{cm}^3 \text{ s}^{-1}$ for Model II,
i.e., for a field installation.
 - c) Expected radius of wetted area in cm (spread) for a field installation.
6. Definitions
- ETA = absolute viscosity
 - HS = depth of soil
 - G = acceleration due to gravity
 - T = gap width between liner and soil
 - AMBDA = Lambda constant, calculated from previous data
 - MMBS10 = evaluates Bessel function from the IMSL Library

```

1. //MODEL JOB (W210,501A,S02,005,PJ),'LEAKRATE'
2. //XBM WATFIV
3. IMPLICIT REAL*8(A-H,O-Z)
4. DIMENSION SPREAD(20),HT(20),HLT(20),Q0(20),H(20),
5. 1 Q1(20),Q2(20)
6. REAL*8 MMBSIO,MMBSI1,MMBSKO,MMBSK1
7. INTEGER IOPT,IER
8. DATA SPREAD/5.D0,10.D0,15.D0,20.D0,25.D0,30.D0,40.D0,
9. 1 50.D0,60.D0,70.D0,80.D0,90.D0,100.D0,200.D0,
10. 2 300.D0,400.D0,500.D0,600.D0,800.D0,1000.D0/
11. 10 READ(5,*,END=1000) NSET,CONDK,TH,R1,N
12. READ(5,*,END=1000) (H(I),I=1,N)
13. RHO=1.00D0
14. ETA=8.95D-03
15. HS = 2.50D 01
16. G = 981.D0
17. PI=3.14159
18. CONST1 = 0.292*DLOG10(CONDK)
19. CONST2 = -0.811+CONST1
20. T = 10.D0**CONST2
21. C -----
22. C CALCULATIONS USING FIELD MODEL
23. C -----
24. WRITE(6,99) NSET
25. 99 FORMAT(///10X,'DATA SET NO..',I3/)
26. WRITE(6,100) R1,TH,T
27. WRITE(6,101) CONDK,ETA
28. 100 FORMAT(/10X,'HOLE DIAMETER =',F10.4/
29. 1 10X,'LINER THICKNESS =',F10.4/
30. 2 10X,'CALCULATED GAP =',F10.4/)
31. 101 FORMAT(/ 10X,'HYDRAULIC COND. OF SOIL =',D10.3/
32. 1 10X,'VISCOSITY OF LEACHATE =',D10.3//)
33. DO 20 I=1,20
34. R2=SPREAD(I)
35. RR=R2/R1
36. H1=0.6835*(CONDK**2)*(RR**4)/G
37. H2=8.0*ETA*CONDK*TH/(R1**2)/RHO/G*(RR**2)
38. H3=3.0*ETA*CONDK*(R1**2)/(T**3)/RHO/G
39. H3=H3*((RR**2)*(2*DLOG(RR)-1)+1)
40. HT(I)=H1+H2+H3
41. Q0(I)=PI*(R2**2)*CONDK
42. C -----
43. C CALCULATIONS USING LAB MODEL
44. C -----
45. R20=3.00D 01
46. IF(R2.LE.R20) R20=R2
47. IOPT =1
48. AMBDA = 12.D0*ETA*CONDK/HS/RHO/G/(T**3)
49. AMBDA = AMBDA**0.5
50. Z1=AMBDA*R1
51. Z2=AMBDA*R20
52. X01=MMBSIO(IOPT,Z1,IER)
53. X12=MMBSI1(IOPT,Z2,IER)
54. X11=MMBSI1(IOPT,Z1,IER)
55. Y01=MMBSKO(IOPT,Z1,IER)
56. Y12=MMBSK1(IOPT,Z2,IER)
57. Y11=MMBSK1(IOPT,Z1,IER)
58. FACT1=Y01+Y12*X01/X12
59. FACT12=Y11/FACT1

```

```

60.      FACT2=X01+X12/Y12*Y01
61.      FACT22=X11/FACT2
62.      FACT3=FACT12-FACT22
63.      FACT0=PI*R1*(T**3)/6.D0/ETA*AMBDA
64.      FACT0=FACT0*RHO*G
65.      HL3=Q0(I)/FACT0/FACT3-HS
66.      HL1=0.06925D0*RHO*(Q0(I)**2)/(R1**4)
67.      HL1=HL1/RHO/G
68.      HL2=2.5465D0*ETA*TH*Q0(I)/(R1**4)
69.      HL2=HL2/RHO/G
70.      HLT(I)=HL1+HL2+HL3
71.      20  CONTINUE
72.          CALL INTERP(HT,Q0,H,Q1,N)
73.          CALL INTERP(HLT,Q0,H,Q2,N)
74.          DO 54 J=1,N
75.              RAD(J)=(Q1(J)/PI/CONDK)**0.5
76.          54  CONTINUE
77.              WRITE(6,201)
78.              WRITE(6,202) (H(I),Q2(I),Q1(I),RAD(I),I=1,N)
79.          201  FORMAT(15X,'  MODEL I ',20X,'  MODEL II ',/,
80.              1      10X,'  HEAD  ', 2X,'  FLOW  ',
81.              2      10X,'  FLOW  ',7X,'  SPREAD ',/)
82.          202  FORMAT( 6X,F10.2,2X,F10.4,9X,F10.4,6X,F10.2)
83.              GO TO 10
84.          1000 CONTINUE
85.              STOP
86.              END
87.              SUBROUTINE INTERP(X0,Y0,CD,Y,NC)
88.              IMPLICIT REAL*8(A-H,O-Z)
89.              DIMENSION X0(20),Y0(20),CD(20),Y(20)
90.              DO 60 K=1,NC
91.                  23  I=1
92.                  24  IF(CD(K)-X0(I)) 27,26,25
93.                  25  I=I+1
94.                  GO TO 24
95.                  26  Y(K)=Y0(I)
96.                  GO TO 60
97.                  27  Y(K)=(Y0(I)-Y0(I-1))/(X0(I)-X0(I-1))*(CD(K)-X0(I-1))+Y0(I-1)
98.                  60  CONTINUE
99.                  RETURN
100.                 END
101.          // $DATA

```

APPENDIX C

CALCULATED FLOW RATES UNDER PERMEAMETER AND FIELD
CONDITIONS

TABLE C1. COMPARISON OF FLOW RATES CALCULATED USING THE PERMEAMETER (I) AND FIELD CONDITIONS (II) FOR $K = 3.40 \times 10^{-4} \text{ CM S}^{-1}$ SOIL

Head (cm)	Flow Rate ($\text{cm}^3 \text{ s}^{-1}$)							
	0.08 cm Diameter		0.16 cm Diameter		0.64 cm Diameter		1.27 cm diameter	
	Hole I	II	Hole I	II	Hole I	II	I	II
10	0.28	0.27	0.40	0.38	0.55	0.52	0.67	0.62
20	0.47	0.46	0.73	0.70	0.99	0.96	1.07	1.12
30	0.62	0.61	1.01	1.00	1.21	1.37	1.31	1.61
40	0.76	0.75	1.18	1.27	1.43	1.78	1.55	2.07
50	0.89	0.87	1.36	1.55	1.65	2.17	1.79	2.52
75	1.11	1.12	1.79	2.18	2.20	3.12	2.39	3.61
100	1.29	1.34	2.20	2.79	2.75	4.06	2.98	4.67
200	1.96	2.08	3.79	4.87	4.94	7.60	5.37	8.69
500	3.37	3.58	7.86	9.71	11.5	17.3	12.5	19.5
750	4.28	4.49	10.8	12.0	17.0	24.9	18.5	28.3
1000	5.07	5.31	12.4	13.9	22.4	32.7	24.4	37.1

TABLE C2. COMPARISON OF FLOW RATES CALCULATED USING THE PERMEAMETER (I) AND FIELD CONDITIONS (II) FOR $K = 3.40 \times 10^{-7} \text{ CM S}^{-1}$ SOIL

Head (cm)	Flow Rate ($\text{cm}^3 \text{ s}^{-1}$)							
	0.08 cm Diameter		0.16 cm Diameter		0.64 cm Diameter		1.27 cm diameter	
	Hole I	II	Hole I	II	Hole I	II	Hole I	II
10	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001
20	0.001	0.001	0.001	0.002	0.001	0.002	0.001	0.002
30	0.001	0.002	0.002	0.002	0.002	0.003	0.002	0.003
40	0.002	0.003	0.002	0.003	0.002	0.004	0.002	0.004
50	0.002	0.003	0.002	0.004	0.002	0.005	0.002	0.005
75	0.003	0.005	0.003	0.006	0.003	0.007	0.003	0.008
100	0.003	0.007	0.003	0.007	0.004	0.009	0.004	0.010
200	0.006	0.012	0.006	0.013	0.007	0.017	0.007	0.019
500	0.014	0.029	0.014	0.032	0.015	0.039	0.016	0.044
750	0.020	0.043	0.021	0.047	0.023	0.056	0.024	0.063
1000	0.026	0.056	0.028	0.061	0.030	0.074	0.031	0.082

APPENDIX D

CALCULATED FLOW RATES AND RADIUS OF WETTED AREA FOR VARIOUS
SIZED HOLES OVER 10^{-4} SUBBASE

TABLE D1. RESULTS FROM FLOW RATE, (Q) AND RADIUS OF WETTED AREA, (R) CALCULATIONS FOR
K = 3.40×10^{-4} CM S⁻¹ SOIL

Head (cm)	0.08 cm Diameter		0.16 cm Diameter		0.64 cm Diameter		1.27 cm diameter	
	Hole Q ₃ -1 cm ³ s ⁻¹	R cm	Hole Q ₃ -1 cm ³ s ⁻¹	R cm	Hole Q ₃ -1 cm ³ s ⁻¹	R cm	Hole Q ₃ -1 cm ³ s ⁻¹	R cm
10	0.27	15.9	0.38	18.8	0.52	22.0	0.62	24.0
20	0.46	20.7	0.70	25.6	0.96	29.9	1.12	32.4
30	0.61	23.9	1.00	30.6	1.37	35.8	1.61	38.7
40	0.75	26.4	1.27	34.5	1.78	40.8	2.07	44.0
50	0.87	28.5	1.55	38.1	2.17	45.0	2.52	48.6
75	1.12	32.4	2.18	45.2	3.12	54.1	3.61	58.2
100	1.34	35.5	2.79	51.1	4.05	61.6	4.67	66.1
200	2.07	44.1	4.87	67.5	7.60	84.4	8.69	90.2
500	3.58	57.9	9.71	95.3	17.2	127	19.4	135
750	4.49	64.8	12.0	106	24.9	153	28.3	163
1000	5.31	70.5	13.9	114	32.7	175	37.1	186

TABLE D2. RESULTS FROM FLOW RATE, (Q) AND RADIUS OF WETTED AREA, (R) CALCULATIONS FOR
K = 3.40×10^{-5} CM S⁻¹ SOIL

Head (cm)	0.08 cm Diameter		0.16 cm Diameter		0.64 cm Diameter		1.27 cm diameter	
	Hole Q ₃ -1 cm ³ s ⁻¹	R cm	Hole Q ₃ -1 cm ³ s ⁻¹	R cm	Hole Q ₃ -1 cm ³ s ⁻¹	R cm	Hole Q ₃ -1 cm ³ s ⁻¹	R cm
10	0.05	21.6	0.06	23.0	0.08	26.5	0.09	28.8
20	0.09	29.7	0.11	31.6	0.14	35.9	0.16	38.9
30	0.14	35.7	0.16	38.1	0.20	43.2	0.23	46.6
40	0.18	40.8	0.20	43.4	0.26	49.2	0.30	52.9
50	0.22	45.1	0.25	48.2	0.32	54.4	0.37	58.4
75	0.31	54.2	0.36	58.1	0.46	65.3	0.52	70.1
100	0.41	61.7	0.47	66.3	0.59	74.5	0.68	79.7
200	0.75	83.9	0.89	91.3	1.11	102	1.25	108
500	1.53	120	2.03	138	2.54	154	2.86	164
750	2.11	140	2.97	167	3.73	197	4.20	198
1000	2.68	159	3.90	191	4.87	214	5.43	226

TABLE D3. RESULTS FROM FLOW RATE, (Q) AND RADIUS OF WETTED AREA, (R) CALCULATIONS FOR
K = 3.40×10^{-6} CM S⁻¹ SOIL

Head (cm)	0.08 cm Diameter		0.16 cm Diameter		0.64 cm Diameter		1.27 cm diameter	
	Hole Q_3 cm ³ s ⁻¹	R cm	Hole Q_3 cm ³ s ⁻¹	R cm	Hole Q_3 cm ³ s ⁻¹	R cm	Hole Q_3 cm ³ s ⁻¹	R cm
10	0.006	24.1	0.007	25.5	0.009	29.2	0.011	31.7
20	0.012	33.2	0.013	35.0	0.017	39.8	0.020	42.9
30	0.017	40.1	0.019	42.2	0.024	47.8	0.028	51.4
40	0.022	45.8	0.025	48.2	0.032	54.4	0.037	58.5
50	0.028	50.8	0.031	53.4	0.039	60.2	0.045	64.5
75	0.040	61.4	0.044	64.5	0.056	72.3	0.064	77.4
100	0.053	70.2	0.058	73.7	0.073	82.4	0.083	88.1
200	0.100	97.0	0.110	102	0.135	112	0.152	119
500	0.233	148	0.256	155	0.313	171	0.353	188
750	0.344	179	0.377	188	0.459	207	0.513	219
1000	0.452	206	0.494	215	0.597	236	0.666	250

TABLE D4. RESULTS FROM FLOW RATE, (Q) AND RADIUS OF WETTED AREA, (R) CALCULATIONS FOR
K = 3.40×10^{-7} CM S⁻¹ SOIL

Head (cm)	0.08 cm Diameter		0.16 cm Diameter		0.64 cm Diameter		1.27 cm diameter	
	Hole	R	Hole	R	Hole	R	Hole	R
	Q_3 cm ³ s ⁻¹	cm	Q_3 cm ³ s ⁻¹	cm	Q_3 cm ³ s ⁻¹	cm	Q_3 cm ³ s ⁻¹	cm
10	0.001	26.7	0.001	28.3	0.001	32.2	0.001	34.9
20	0.001	36.8	0.002	38.8	0.002	43.9	0.002	47.4
30	0.002	44.4	0.002	46.8	0.003	52.8	0.003	56.8
40	0.003	50.8	0.003	53.4	0.004	60.2	0.004	64.5
50	0.003	56.4	0.004	59.3	0.005	66.5	0.005	71.3
75	0.005	68.1	0.006	71.5	0.007	80.1	0.009	85.5
100	0.007	77.9	0.007	81.7	0.009	91.3	0.008	97.4
200	0.012	107	0.013	112	0.017	124	0.019	132
500	0.029	165	0.032	172	0.039	191	0.044	202
750	0.043	200	0.047	209	0.056	230	0.063	242
1000	0.056	229	0.060	239	0.074	262	0.082	277

APPENDIX E

TEST RESULTS FROM ELEVATED HEAD APPARATUS

FLOW RATES AT ELEVATED HEADS

An attempt was made to study the effect of substantially increased head on the discharge through flaws in a synthetic liner. The pressure vessel described in Figure 3 was used in place of the barrel to determine the effect of greater head.

Three runs were made using a 0.076 cm HDPE liner with a 0.63 cm circular hole. Each run was under a pressure of 0.1034 MPa or the equivalent of a 10 meter head of water. Prior to using the elevated head, the soil in Tub 4 was run through the normal conductivity check using the barrel. The conductivity was 1.6×10^{-7} cm sec⁻¹.

The 10 meter head was then applied by imposing air pressure on the water over to the liner. Head measurements were taken through the sight tube over a five day period. Evidence of erosion was observed when the soil and liner were examined following the test.

A 1.3 cm deep parabolic hole was observed in the soil of Tub 4 beneath the liner flaw (Figure E1). The radius of the hole ranged from 2.1 cm at the surface to 0.5 cm at the base. In addition to the hole, numerous erosion paths radiated from the hole to a distance of about 20 cm, with the tub radius being 30 cm. The maximum depth of these paths was 0.3 cm.

A general compression of the soil was also noted. The soil had compressed 0.3 cm near the center and one cm near the edges. The soil had a meniscus shape adjacent to the walls, apparently due to the support given the liner by the flange.

Another try at the test yielded the same results (Figure E2). Tub 5 was run under the 10 meter head for seven days. A hole again formed in the soil beneath the liner flaw. This hole was dish shaped with a

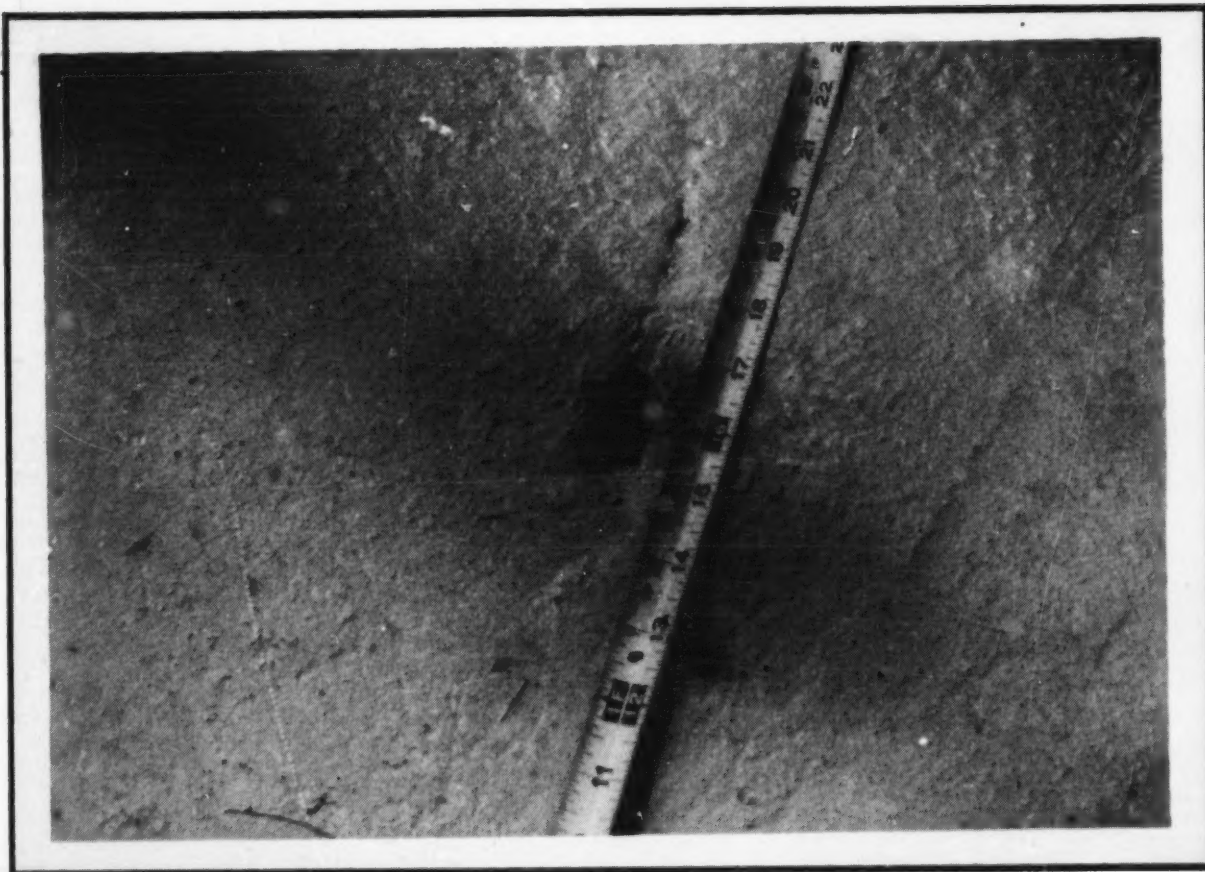
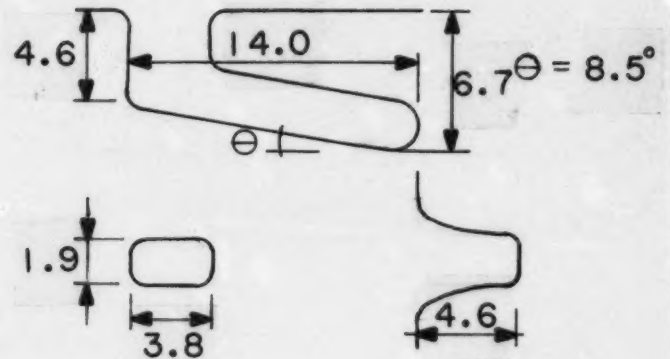


Figure E1. Photograph of eroded hole under a 0.764 diameter round flaw in 0.08 cm HDPE over 10^{-7} subbase at head of 0.1034 MPa (10 m of water).

A

0.08 cm HDPE
0.64 cm Round Hole
 10^{-7} Subbase
0.1034 MPa for 65.5 hr

**B**

0.08 cm HDPE
0.64 cm Round Hole
 10^{-7} Subbase
0.1034 MPa for 157.4 hr

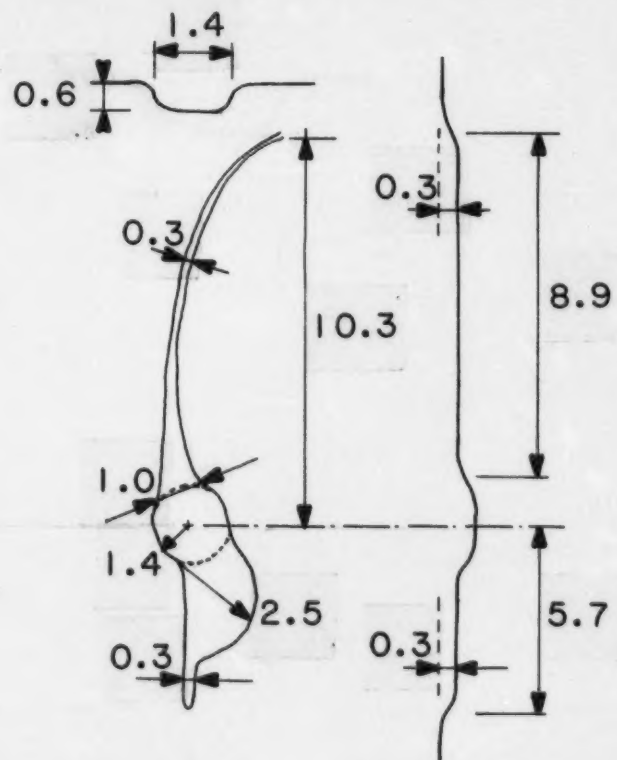


Figure E2. Diagrams of holes formed beneath FMLs overlying a 10^{-7} subbase.

surface radius of 1.4 cm and a depth of 0.6 cm. However, much larger soil surface erosion was present. A small erosion pathway, 0.3 cm deep and 0.3 cm wide, extended 8.9 cm radially to one side from the edge of the hole. Another shorter eroded area about 4 cm long was also observed opposite the aforementioned hole.

Tub 6 was tested in a different manner. The tub had about 100 cm head on it for 20 days prior to attaching the pressure vessel. During this time, no change in fluid head was observed. A conductivity check was performed under the 10 meter head, yielding a conductivity of 2.0×10^{-7} cm sec⁻¹. No deformations or erosion channels were observed in the soil. The test was then run with the HDPE liner for four days. When the liner was removed, a slight elongation of the 0.63 cm circular flaw was observed. The soil, as with Tubs 4 and 5, was eroded under the flaw in the liner. Like the elongated liner hole, this eroded area was oval with surface dimensions of 1.9 by 3.8 cm and extended 4.6 cm deep (Figure E2a). At this depth, the hole made a right angle turn and continued a slight downward path an additional 14 cm to a final depth of 6.7 cm. This is the most serious case of observed erosion. The right angle turn most likely occurred at an interface between compaction lifts. It is not evident to what depth the crater would have continued in a more isotropic soil.

A 0.25 cm HDPE liner with a 0.64 cm round hole under elevated head for 39 hr resulted in the formation of an eroded hole approximately 2.9 cm diameter and 0.7 cm deep in the more permeable sandy soil ($K = 10^{-4}$) (Figure E3c). A 0.08 cm PVC liner with a similar hole, subbase, and head eroded a 1.6 cm diameter by 0.5 cm deep hole in the soil in 204 hours (Figure E4a). A 0.08 cm PVC liner with similar hole, subbase, and

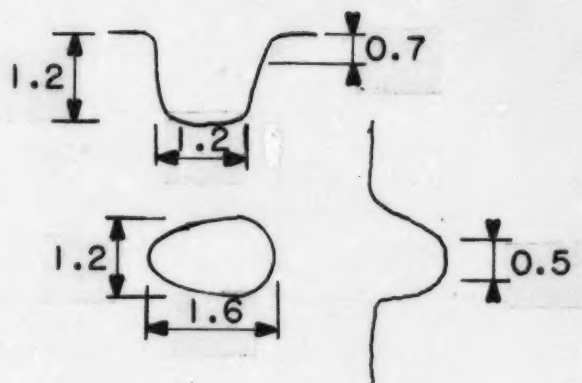
A

0.11 cm CSPE

0.16 cm Round Hole

 10^{-4} Subbase

0.1034 MPa for 47.6 hr

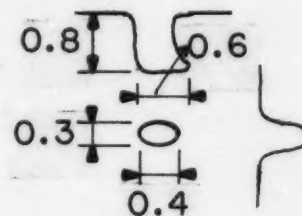
**B**

0.11 cm CSPE

0.08 cm Round Hole

 10^{-4} Subbase

0.1034 MPa for 19 hr

**C**

0.25 cm HDPE

0.64 cm Round Hole

 10^{-4} Subbase

0.1034 MPa for 39 hr

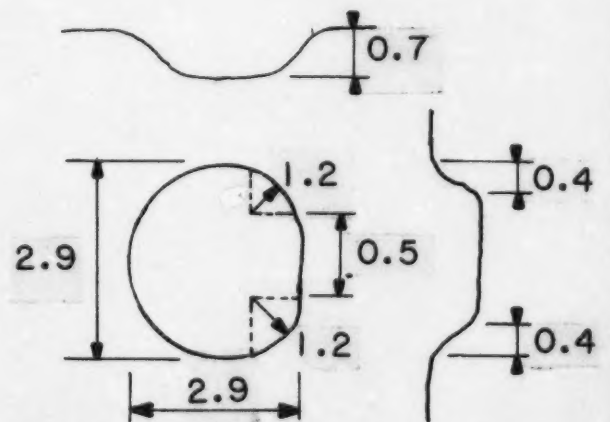
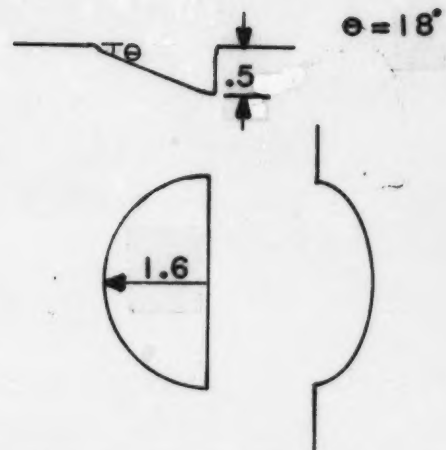


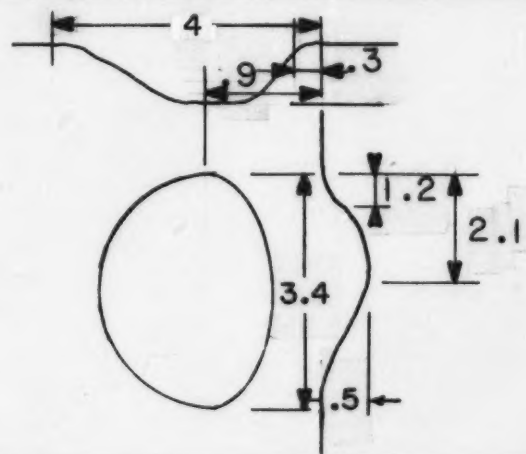
Figure E3. Diagrams of holes formed beneath FMLs overlying 10^{-4} subbase.

A

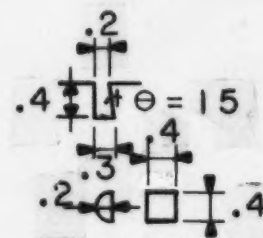
0.08 cm PVC
 0.64 cm Round Hole
 10⁻⁴ Subbase
 0.1034 MPa for 204.5 hr

**B**

0.08 cm EPDM
 0.64 cm Round Hole
 10⁻⁴ Subbase with Geotextile
 0.1034 MPa for 26 hr

**C**

0.09 cm CSPE
 0.08 cm Round Hole
 10⁻⁴ Subbase
 0.1034 MPa for 19.5 hr

**D**

0.09 cm CSPE
 5 cm Slit
 10⁻⁴ Subbase
 0.1034 MPa for 47.5 hr

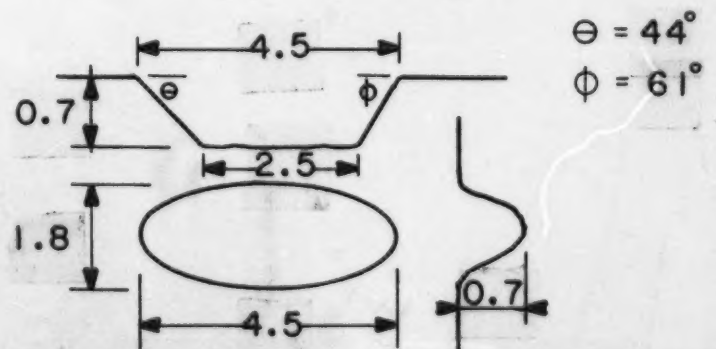


Figure E4. Diagrams of holes formed beneath FMLs overlying 10⁻⁴ subbase.

head eroded a 4 cm diameter and 3.4 cm deep hole in the soil in 26 hr, even in the presence of a geotextile on top of the subbase (Figure E4b).

Testing the erosion from small holes was done using 0.11 cm CSPE material. A 0.08 cm diameter round hole that was under elevated head for 19 hr resulted in a hole approximately 0.4 cm in diameter and depth (Figure E4c). A second replication of this treatment eroded a hole 0.4 to 0.6 cm in diameter and 0.8 cm deep in 19 hours (Figure E3b). A 0.16 cm diameter round hole in 0.11 cm CSPE under elevated head for 47.6 hr caused enough erosion to form a hole measuring 1.2 to 1.6 cm in diameter and 1.2 cm in depth (Figure E3a). A 5 cm long vertical slit in 36 mil CSPE resulted in the erosion of an elliptical shaped hole 4.5 cm long, 1.8 cm wide, and 0.7 cm deep (Figure E4d).

This evidence of erosion caused by water flowing through flaws in liners under elevated head is a serious concern, since erosion of the subbase may result in stretching and the eventual rupture of the FML. Therefore, the calculational procedure was adapted to predict the conditions necessary for erosion to begin.

THE USE OF THE MODEL CALCULATIONAL PROCEDURE TO PREDICT CONDITIONS FOR INITIATION OF EROSION

An attempt was made to predict the incipient conditions of subbase erosion by using the calculational procedure that was developed for determining flow rates in the permeameters. In this analysis, the critical tractive force approach was used. The derivation of the equations for the tractive force is as follows:

From Equation (4), the tractive force exerted by the fluid flow on the surface of the soil can be expressed as:

$$\tau_o = - \frac{t}{2} \frac{dp}{dr} \quad (64)$$

Combining this relationship with (12),

$$\tau_o = \frac{3\eta}{\pi r t^2} Q \quad (65)$$

Using the result obtained for Q in (31),

$$\text{Tractive force, } \tau_o = \frac{\lambda t}{2} [B K_1(\lambda r) - A I_1(\lambda r)] \quad (66)$$

This can be transformed to non-dimensional form by dividing by $\pi t^3 p_3 / 6\eta$.

$$\tau_o = \frac{\lambda t}{2} [B K_1(\lambda r) - A I_1(\lambda r)] \quad (67)$$

The result obtained in Equation (67) are shown graphically in Figure (E5). The tractive force exerted by the fluid flow on the soil surface decreases asymptotically with increasing radial distance. Thus, the maximum tractive force occurs at the immediate vicinity of the liner flaw. The calculated values of the maximum tractive force for each permeameter test are listed in Tables E1 and E2.

To predict the incipient conditions of erosion, it is necessary to have a knowledge of the erosion resistance (or the critical tractive force) for the soil. Studies have been conducted to determine the critical tractive force for cohesive soils and to investigate how the resistance of the soil varies with the degree of compaction, clay content, etc. The results obtained from a study by Raudkivi (1967) are shown in Figure E5. Other experimental studies have been conducted to determine the influence of properties such as particle size, plasticity

TABLE E1. COMPARISON OF FLOW RATES FOR $K = 10^{-4}$
 CM S^{-1} SOIL

TAG	LINER THICK CM	FLAW DIA. CM	HYD.COND. CM/S	HEAD CM	Q-OBS CC/S	Q-CALC CC/S	Q-DIFF CC/S	TRACTION DYNES/SQ.CM
192	0.0762	0.08	0.327D-03	79.2	1.045	1.010	-0.035	966.4*
193	0.0762	0.08	0.327D-03	77.6	1.056	1.005	-0.051	962.1*
194	0.0762	0.08	0.196D-03	75.0	0.864	0.969	0.105	926.8*
13	0.0762	0.16	0.564D-03	75.1	1.170	2.190	1.020	1047.5*
14	0.0762	0.16	0.343D-03	73.5	1.750	1.746	-0.004	835.2*
15	0.0762	0.16	0.151D-03	74.9	1.307	1.087	-0.220	520.1*
7	0.0762	0.64	0.120D-03	73.2	0.765	0.978	0.213	117.0
9	0.0762	0.64	0.120D-03	75.3	1.290	0.999	-0.291	119.5
10	0.0762	1.27	0.583D-03	73.7	3.810	3.060	-0.750	182.9
11	0.0762	1.27	0.153D-03	70.1	2.331	1.199	-1.132	71.7
12	0.0762	1.27	0.323D-03	72.4	2.320	2.127	-0.193	127.2
45	0.2032	0.64	0.114D-03	76.6	2.763	0.971	-1.792	116.1
46	0.2032	0.64	0.556D-03	70.7	2.614	2.611	-0.003	312.3*
47	0.2032	0.64	0.323D-03	78.6	2.718	2.099	-0.619	251.0
59	0.2540	0.16	0.258D-03	78.3	0.988	1.573	0.585	752.6*
70	0.2540	0.16	0.251D-03	71.9	2.710	1.455	-1.255	696.0*
71	0.2540	0.16	0.258D-03	75.0	1.968	1.524	-0.444	729.0*
48	0.2540	0.64	0.340D-03	77.2	2.463	2.136	-0.327	255.5
49	0.2540	0.64	0.525D-03	75.3	3.087	2.687	-0.400	321.4*
50	0.2540	0.64	0.235D-03	71.4	2.816	1.589	-1.227	190.0
33	0.0508	0.64	0.210D-03	80.4	1.243	1.606	0.363	192.1
34	0.0508	0.64	0.299D-03	75.2	1.165	1.935	0.770	231.4
35	0.0508	0.64	0.343D-03	78.9	1.202	2.183	0.981	261.1
30	0.0762	0.64	0.413D-03	78.7	1.793	2.425	0.632	290.0*
42	0.0762	0.64	0.583D-03	77.6	1.035	2.863	1.828	342.4*
43	0.0762	0.64	0.441D-03	80.3	0.575	2.552	1.977	305.2*
44	0.0762	0.64	0.343D-03	71.5	0.955	2.027	1.072	242.5
36	0.0914	0.64	0.323D-03	76.4	1.116	2.054	0.938	245.7
37	0.0914	0.64	0.340D-03	77.7	0.872	2.146	1.274	256.7
38	0.0914	0.64	0.441D-03	77.7	0.652	2.489	1.837	297.7*
39	0.1143	0.64	0.136D-03	76.1	1.354	1.113	-0.241	133.1
40	0.1143	0.64	0.153D-03	71.9	0.971	1.169	0.198	139.8
41	0.1143	0.64	0.546D-03	75.0	1.756	2.731	0.975	326.7*

TABLE E2. COMPARISON OF FLOW RATES FOR $K = 10^{-7}$
CM S⁻¹ SOIL

TAG	LINER THICK CM	FLAW DIA. CM	HYD.COND. CM/S	HEAD CM	Q-OBS CC/S	Q-CALC CC/S	Q-DIFF. CC/S	TRACTION DYNES/SQ.CM
13	0.0762	0.16	0.823D-06	75.0	0.00680	0.00436	-0.00244	117.2
14	0.0762	0.16	0.506D-06	75.0	0.00323	0.00329	0.00006	88.6
15	0.0762	0.16	0.823D-06	75.0	0.00589	0.00436	-0.00153	117.2
4	0.0762	0.64	0.758D-06	75.0	0.00558	0.00477	-0.00081	32.1
5	0.0762	0.64	0.506D-06	75.0	0.00532	0.00365	-0.00167	24.6
6	0.0762	0.64	0.758D-06	75.0	0.00421	0.00477	0.00056	32.1
10	0.0762	1.27	0.452D-06	75.0	0.00245	0.00355	0.00110	11.9
11	0.0762	1.27	0.446D-06	75.0	0.00220	0.00352	0.00132	11.8
12	0.0762	1.27	0.446D-06	75.0	0.00319	0.00352	0.00033	11.8
45	0.2032	0.64	0.452D-06	75.0	0.00250	0.00337	0.00087	22.7
46	0.2032	0.64	0.446D-06	75.0	0.00315	0.00334	0.00019	22.5
47	0.2032	0.64	0.506D-06	75.0	0.00457	0.00365	-0.00092	24.6
69	0.2540	0.16	0.758D-06	75.0	0.00490	0.00417	-0.00073	112.3
70	0.2540	0.16	0.540D-06	75.0	0.00266	0.00343	0.00077	92.3
71	0.2540	0.16	0.823D-06	75.0	0.00618	0.00436	-0.00182	117.2
48	0.2540	0.64	0.823D-06	75.0	0.00533	0.00502	-0.00031	33.8
49	0.2540	0.64	0.446D-06	75.0	0.00407	0.00334	-0.00073	22.5
50	0.2540	0.64	0.452D-06	75.0	0.00316	0.00337	0.00021	22.7
90	0.2540	1.27	0.230D-06	75.0	0.00171	0.00204	0.00033	6.9
91	0.2540	1.27	0.452D-06	75.0	0.00299	0.00355	0.00056	11.9
92	0.2540	1.27	0.446D-06	75.0	0.00471	0.00352	-0.00119	11.8
33	0.0508	0.64	0.823D-06	75.0	0.00171	0.00502	0.00331	33.8
34	0.0508	0.64	0.506D-06	75.0	0.00472	0.00365	-0.00107	24.6
35	0.0508	0.64	0.506D-06	75.0	0.00387	0.00365	-0.00022	24.6
30	0.0762	0.64	0.601D-06	75.0	0.00459	0.00411	-0.00048	27.7
31	0.0762	0.64	0.506D-06	75.0	0.00450	0.00365	-0.00085	24.6
32	0.0762	0.64	0.758D-06	75.0	0.00341	0.00477	0.00136	32.1
43	0.0762	0.64	0.446D-06	75.0	0.00364	0.00334	-0.00030	22.5
44	0.0762	0.64	0.823D-06	75.0	0.00500	0.00502	0.00002	33.8
183	0.0914	0.08	0.506D-06	75.0	0.00338	0.00314	-0.00024	168.8
184	0.0914	0.08	0.230D-06	75.0	0.00250	0.00182	-0.00068	97.9
185	0.0914	0.08	0.758D-06	75.0	0.00260	0.00392	0.00132	211.2
57	0.0914	0.16	0.823D-06	75.0	0.00452	0.00436	-0.00016	117.2
58	0.0914	0.16	0.452D-06	75.0	0.00307	0.00306	-0.00001	82.3
59	0.0914	0.16	0.758D-06	75.0	0.00338	0.00417	0.00079	112.3
36	0.0914	0.64	0.823D-06	75.0	0.00619	0.00502	-0.00117	33.8
37	0.0914	0.64	0.452D-06	75.0	0.00422	0.00337	-0.00085	22.7
38	0.0914	0.64	0.758D-06	75.0	0.00467	0.00477	0.00010	32.1
78	0.0914	1.27	0.452D-06	75.0	0.00312	0.00355	0.00043	11.9
79	0.0914	1.27	0.446D-06	75.0	0.00243	0.00352	0.00109	11.8
80	0.0914	1.27	0.540D-06	75.0	0.00314	0.00406	0.00092	13.6
39	0.1143	0.64	0.506D-06	75.0	0.00357	0.00365	0.00008	24.6
40	0.1143	0.64	0.823D-06	75.0	0.00586	0.00502	-0.00084	33.8
41	0.1143	0.64	0.452D-06	75.0	0.00284	0.00337	0.00053	22.7

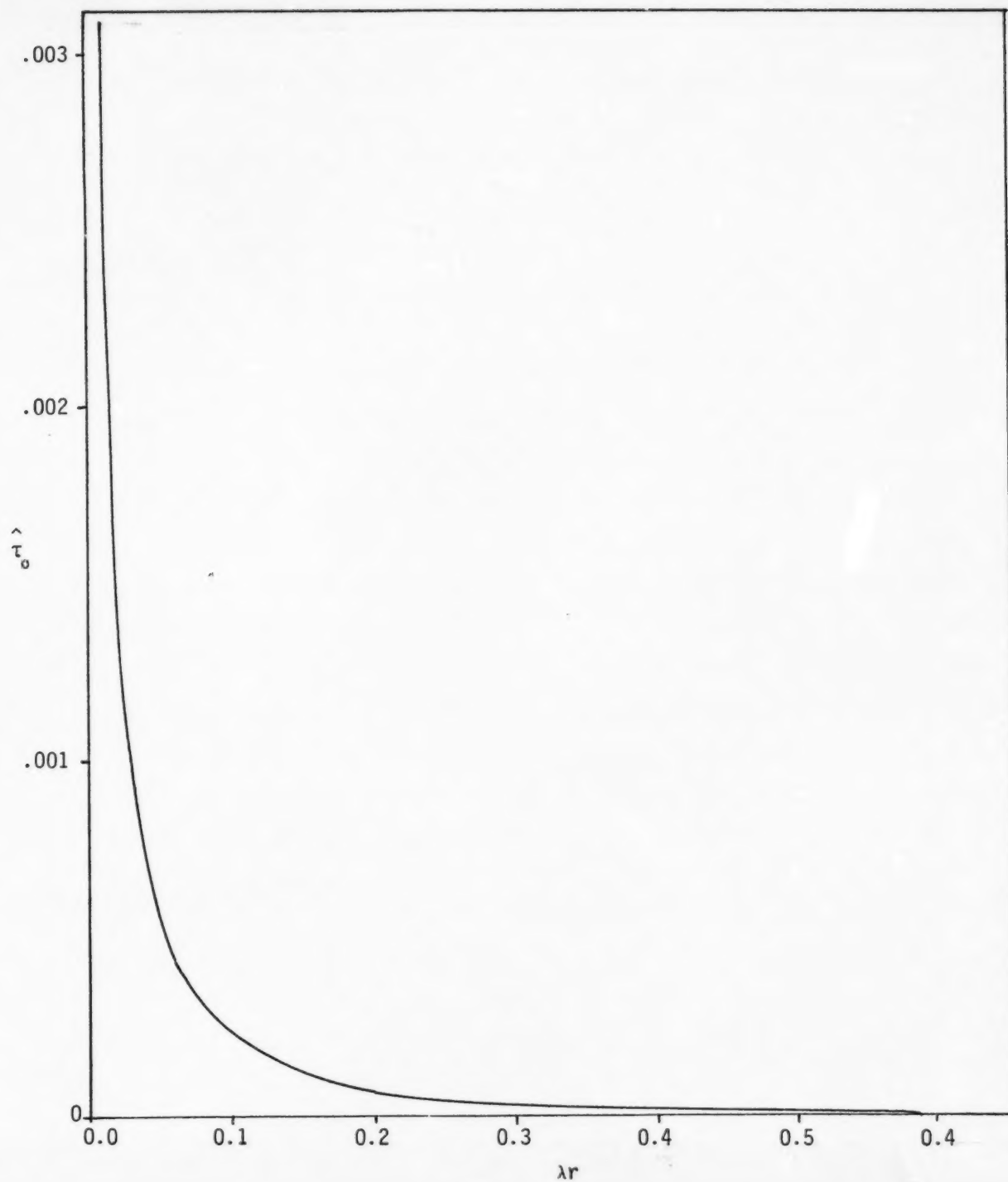


Figure E5. Non-dimensional tractive force vs λr .

index, and cation exchange capacity on the resistance of soil to erosion. These results, however, have been reported for materials that were in a much looser state than the compacted soil used in the permeameter tests. Assuming the compacted subsoil to be in the very dense region and the clay fraction to be 50%, the critical tractive force for the soil can be determined from Figure E6 as 0.6 psf (289 dynes/cm²). In Tables E1 and E2, asterisks (*) denote the permeameter test conditions where the calculated maximum tractive force has exceeded the aforementioned critical value.

The actual test results showed that the erosion was less prevalent than predicted by these calculations. However, the calculational procedure was capable of predicting the following trends that agreed with observed behavior:

1. The variation of tractive force with radial distance shown in Figure (E5) suggests that erosion can be expected to occur in a highly localized region close to the liner flaw.
2. The maximum tractive forces tabulated above clearly indicate that erosion is much more likely to occur in the 10^{-4} cm s⁻¹ permeability soil than in the 10^{-7} cm s⁻¹ permeability soil. None of the tractive force values calculated for the 10^{-7} cm s⁻¹ material at heads of 100 cm or less reached the critical value of erosion. This agrees well with the observations made during testing. However, it should be noted that erosion of 10^{-7} cm s⁻¹ soil has occurred in tests with elevated heads (10 m).

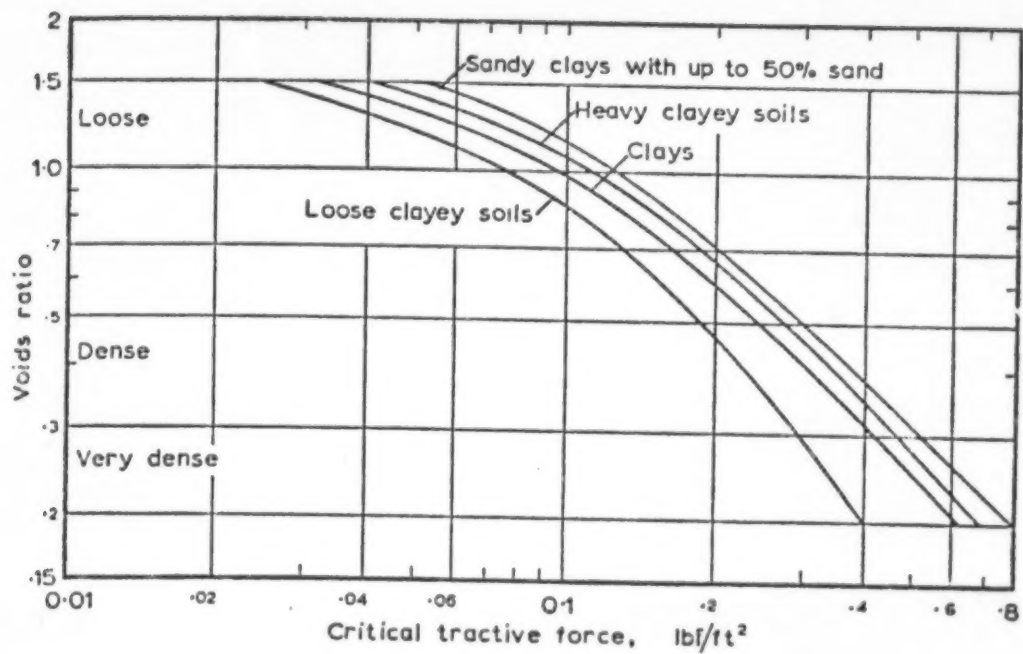


Figure E6. The critical tractive force for cohesive soils (Raudkivi, 1967).

3. It can also be noted that the calculated tractive forces are much larger in magnitude for small diameter holes than for the large diameter flaws. This suggests that there will be a greater tendency for erosion to occur at small diameter holes. This prediction is supported by the observations made during testing.